Appendix VII

Climate Warming and California's Water Future

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Preface

In Hades, the mythical Tantalus was burdened by a great thirst, only to have the water rise to his neck and threaten to drown him, then recede when he tried to drink. At the same time, ever present above him was a large rock, ready to crush his head at any moment. Like Tantalus, California's water managers are tantalized by the prospects of quenching California's thirsts, but must constantly contend with floods and droughts as they cope with a world of such grave prospects as earthquakes, government budgets, population growth, and climate changes.

This appendix presents the method and results of an application of the CALVIN economic-engineering optimization model to offer insights into the potential effects of climate changes on California water management in the distant future (2100). Much will happen in California in the coming 100 years. No one can be sure exactly what will happen, but prudence asks that we examine a range of reasonable scenarios.

Although this time frame is distant and well beyond the careers (and lifetimes) of most readers and far beyond the election cycles of political leaders, 2100 is not beyond the lifetime of most water management infrastructure (dams, canals, and rivers) or many of the institutions that govern water management. A century is also not an unreasonable amount of time in which to develop and establish extensive innovations in water management. The first plan for large-scale irrigation in the Central Valley dates from 1873. Major elements modified from this plan were not in place until the 1940s and 1950s. As population, activity, and human expectations continue to increase in California, the time needed to make major infrastructure and water management changes may increase as well.

This project is part of a major multidisciplinary effort to examine possible water-related impacts of climate change on California, and potential adaptations of Californians to respond to such changes. Robert Mendelson (Yale University), Tom Wilson (Electric Power Research Institute [EPRI]), and Joel Smith (Stratus Consulting), led the project, under program manager Guido Franco (California Energy Commission [Commission]). The work presented here relies on data and information provided by John Landis (University of California, Berkeley), Norm Miller (Lawrence Berkeley National Laboratory [LBNL]), Russell Jones (Stratus Consulting), and Richard Adams (Oregon State University), and relies extensively on earlier work on the CALVIN model, funded by CALFED and the State of California Resources Agency.

We greatly appreciate the insights, comments, corrections, and suggestions from Guido Franco (Commission), Alan Sanstad (LBNL), Maury Roos (Department of Water Resources [DWR]), and Doug Osugi (DWR), who reviewed drafts of this report. Jamie Anderson (DWR) is thanked for her examination of climate change operations for delta water quality implications.

Executive Summary

In California, concern for climate change has increased in recent years as research on global climate change has been applied to the state and as it has become apparent that California's climate has changed recently (Dettinger and Cayan, 1995; Gleick and Chalecki, 1999; Lower American River flood frequencies) and in recent millennia (Stine, 1994). Several decades of studies have shown that California's climate has varied historically and continues to vary today (Cayan et al., 1999), is experiencing continuing sea level rise, and may experience significant climate warming (Lettenmaier and Gan, 1990; Snyder et al., 2002). The potential effects of climate change on California have been widely discussed from a variety of perspectives (Lettenmaier and Sheer, 1991; Gleick and Chalecki, 1999; Wilkinson, 2002). Forests, marine ecosystems, energy use, coastal erosion, water availability, flood control, and general water management issues have all been raised.

This study focuses on the likely effects of a range of climate warming estimates on the long-term performance and management of California's water system. We take a relatively comprehensive approach, looking at the entire intertied California water supply system, including ground and surface waters, agricultural and urban water demands, environmental flows, and hydropower. In addition, we examine the potential for managing the water supply infrastructure to adapt to changes in hydrology caused by climate warming. We use an integrated economic-engineering optimization model of California's intertied water system called CALVIN (CALifornia Value Integrated Network), which has been developed for general water policy, planning, and operations studies (Jenkins et al., 2001; Draper et al., in press). This modeling approach allows us to look at how well the infrastructure of California water could respond and adapt to changes in climate, in the context of higher future populations, changes in land use, and advances in agricultural technology. Unlike traditional simulation modeling approaches, this economically optimized reoperation of the system to adapt to climate and other changes is not limited by present-day water system operating rules and water allocation policies, which by 2100 are likely to be seen as archaic. This approach has its own limitations, but offers useful insights on the potential for operating the current or proposed infrastructure for very different conditions in the future (Jenkins et al., 2001, Chapter 5).

Project Method

Many types of climate change can affect water and water management in California. In this study, we examined climate warming and neglected climate variability, sea level rise, and other forms of climate change. To develop integrated statewide hydrologies that cover changes in all major inflows to the California water system, we examined 12 climate warming hydrologies. For each climate warming scenario, researchers at Lawrence Berkeley National Laboratory (LBNL) developed permutations of historical flow changes for six representative basins throughout

California (Miller et al., 2001). These changes were used as index basins for 113 inflows to the CALVIN model (Figure ES.1). This more comprehensive hydrology includes inflows from mountain streams, groundwater, and local streams, as well as reservoir evaporation for each of the 12 hydrologies. The gross implications of these changes in California's water availability are then estimated, including effects of forecasted changes in 2100 urban and agricultural water demands.

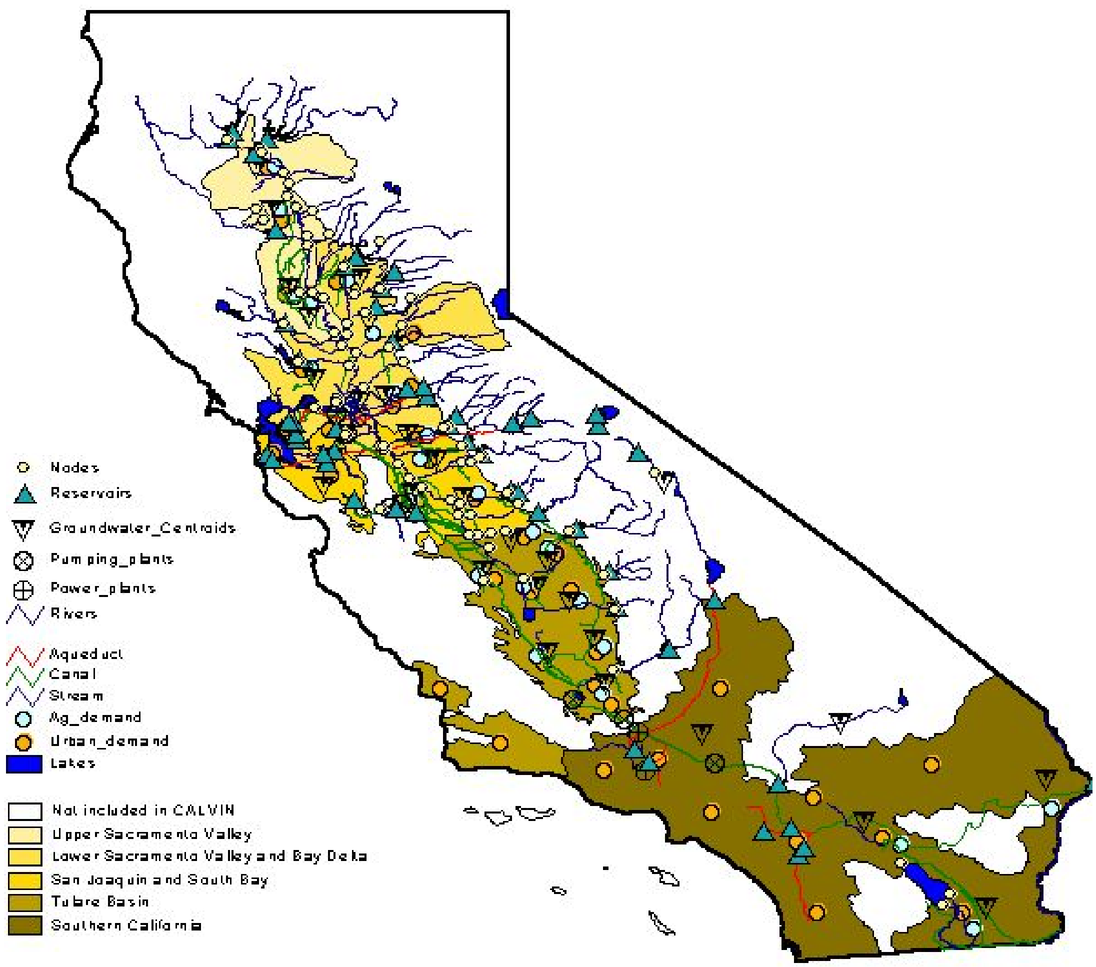

Figure ES.1. Demand areas and major inflows and facilities represented in CALVIN.

Because of limited time and budget, we explicitly modeled only two of these climate warming scenarios using CALVIN. For this particular climate change study, for the 2100 time horizon with 2100 demands, we made a number of modifications to the CALVIN model:

- Changes in hydrology and water availability were made for surface and groundwater sources throughout the system to represent different climate warming scenarios.
- Estimates of 2100 urban and agricultural economic water demands were used.
- Coastal areas were given unlimited access to sea water desalination at a constant unit cost of $1,400/acre-ft.
- Urban wastewater reuse was made available beyond 2020 levels at $1,000/acre-ft, up to 50% of urban return flows.
- Local well, pumping, and surface water diversion, connection, and treatment facilities were expanded to allow access to purely local water bodies at appropriate costs.
- Several corrections to the earlier CALFED version of the model were made, including revising environmental requirements on system operations.

The method employed for this study contributes several advances over previous efforts to understand the long-term effects of climate warming on California's water system, as well as long-term water management with climate change in general. These include:

- **Comprehensive hydrologic effects of climate warming.** These effects include all major hydrologic inputs — major streams, groundwater, and local streams — as well as reservoir evaporation. Groundwater, in particular, represents 30%-60% of California's water deliveries and 17% of natural inflows to the system.
- **Integrated consideration of groundwater storage**. Groundwater contributes well over half of the storage used in California during major droughts.
- **Statewide impact assessment**. Previous explorations of climate change's implications for California examined only a few isolated basins or one or two major water projects. However, California has a very integrated and extensive water management system, which continues to be increasingly integrated in its planning and operations over time. Evaluating the ability of this integrated system to respond to climate change is likely to require that the entire system be examined.

- **Economic-engineering perspective**. In this context, water in itself is not important. It is the ability of water sources and a water management system to supply water for environmental, economic, and social purposes that is the relevant measure of the effect of climate change and adaptations to climate change. Traditional "yield"-based estimates of climate change effects do not yield results as meaningful as economic and delivery-reliability indicators of performance.

- **Integration of multiple responses**. Adaptation to climate change will not be through a single option, but through a concert of many traditional and new water supply and management options. The CALVIN model explicitly represents and integrates a wide variety of response options.

- **Incorporation of future growth and change in water demands**. Climate change will have its greatest effects some decades from now. During this time, population growth and other changes in water demands are likely to exert major influences on how water is managed in California and on how well the system performs.

- **Optimization of operations and management**. Most previous studies of the impact of climate change on water management have been simulation-based. Because major climate changes are most likely to occur only after several decades, it seems unreasonable to employ current system operating rules in such studies. Fifty years from now, today's rules will be archaic (Johns, 2003). Water management systems commonly adapt to changing conditions, especially over long time periods, making an optimization approach seem more reasonable. Optimization approaches do have limitations (Jenkins et al., 2001), particularly their optimistic view of what can be done. However, the limitations of optimization seem less burdensome than the limitations of simulation for exploratory analysis of climate change policy and management problems.

Results

In the sections that follow, we present the overall supply and demand results of this study, along with model results that estimate the effects of climate and population change on the performance of California's intertied water supply system.

Changes in water demands

An important aspect of future water management is future water demands. California's population continues to grow and its urban areas continue to expand, with likely implications for urban and agricultural water demands. Population growth in California is expected to continue from today's 32 million, to 45 million in 2020, to an estimated at 92 million for 2100 (the high

Table ES.1. Land and applied water demands for California's intertied water system (millions of acres and millions of acre-feet [MAF]/yr)

Use	2020 land	2100 land	2020-2100 decrease	2020 water	2100 water	2020-2100 change
Urban				11.4	18.6	+7.2
Agricultural	9.2	8.4	0.75	27.8	25.1	-2.7
Environmental	-	-	-	-	-	-
Total	-	-	-	**39.9**	**44.5**	**+4.5 MAF/yr**

population scenario for the larger study — the lower scenario is 67 million). The demands in the intertied system (Table ES.1) represent about 90% of those in California.

Changes in California's water supplies

Table ES.2 shows the 12 climate warming scenarios we examined, along with their overall effects on water availability. Although these are merely raw hydrologic results, adjusted for groundwater storage effects, they indicate a wide range of potential water supply impacts on California's water supply system. These effects range from +4.1 MAF/yr to -9.4 MAF/yr. Figure ES.2 shows the seasonal hydrologic streamflow results for the 12 warming scenarios for mountain rim inflows, about 72% of California system inflows. For all cases spring snowmelt is greatly decreased with climate warming, and winter flows are generally increased (except for some parallel climate model [PCM] scenarios). These results indicate the overall hydrologic effect of climate warming on inflows to California's water supplies. These seasonal changes in runoff have long been identified, based on studies of individual basins or a few basins (Lettenmaier and Gan, 1990).

Table ES.2. Raw water availability (without operational adaptation, in MAF/yr)

	Average annual water availability			Average annual water availability	
Climate scenario	**Volume (MAF)**	**Change MAF (%)**	**Climate scenario**	**Volume (MAF)**	**Change MAF (%)**
1. 1.5 temperature (T) 0% precipitation (P)	35.7	-2.1 (-5.5)	7. HadCM2[a] 2010-2039	41.9	4.1 (10.8)
2. 1.5 T 9% P	37.7	-0.1 (-0.4)	8. HadCM2 2050-2079	40.5	2.7 (7.2)
3. 3.0 T 0 %P	33.7	-4.1 (-10.9)	9. HadCM2 2080-2099	42.4	4.6 (12.1)
4. 3.0 T 18% P	37.1	-0.8 (-2.0)	10. PCM 2010-2039	35.7	-2.1 (-5.6)
5. 5.0 T 0% P	31.6	-6.2 (-16.5)	11. PCM 2050-2079	32.9	-4.9 (-13.0)
6. 5.0 T 30% P	36.2	-1.6 (-4.3)	12. PCM 2080-2099	28.5	-9.4 (-24.8)
Historical	**37.8**	**0.0 (0.0)**			

a. Hadley Climate Centre's model.

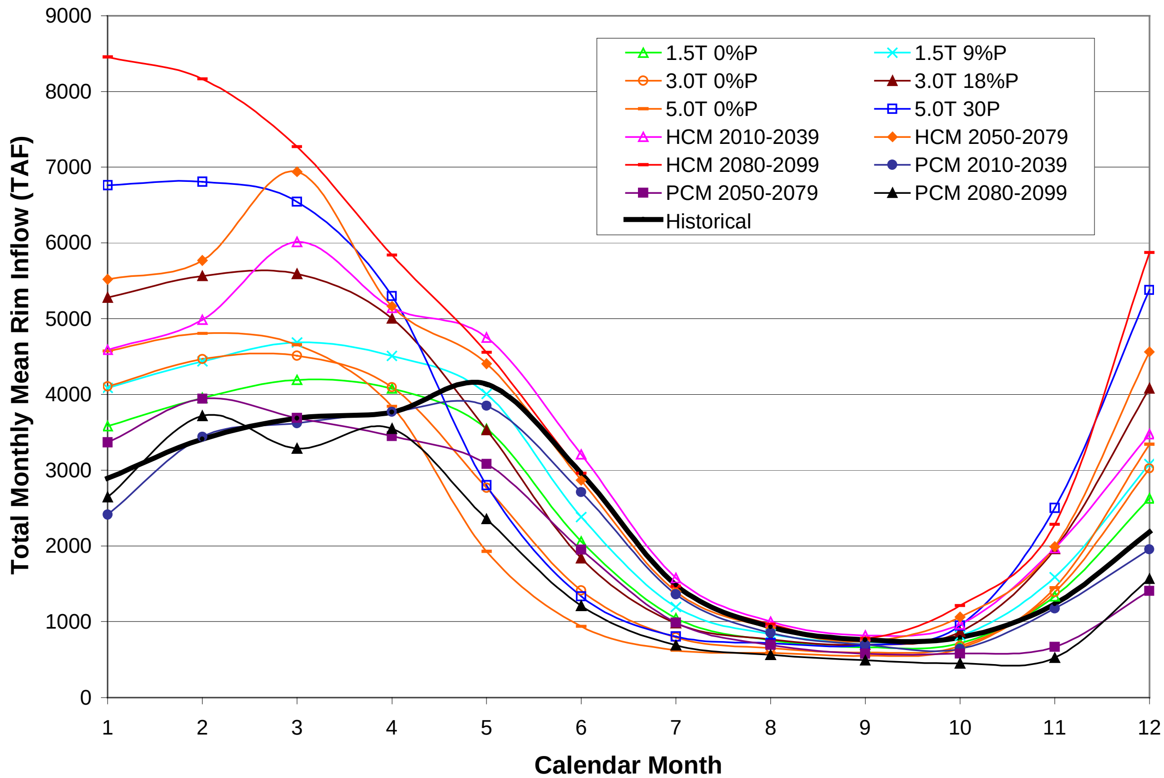

Figure ES.2. Monthly mean rim inflows for the 12 climate scenarios and historical data.

Adaptive changes for water management

California has a diverse and complex water management system with considerable long-term physical flexibility. Californians are becoming increasingly adept at developing and integrating many diverse water supply and demand management options locally, regionally, and even statewide. The mix of options available to respond to climate change, population growth, and other challenges is likely to increase in the future with further development of water supply and demand management technologies, such as improved wastewater and desalination treatment methods and water use efficiency techniques.

Using the CALVIN model, we ran several statewide scenarios to evaluate the potential impact of climate change on California with and without population growth and adaptation. The modeled scenarios included:

- **Base 2020**: This run represents projected water supply operations and allocations in 2020, assuming that current operation and allocation policies continue. This run was prepared for CALFED and is extensively documented elsewhere (Jenkins et al, 2001; Draper et al., in press).

- **SWM (Statewide Water Market) 2020**: This run represents operations, allocations, and performance in 2020, assuming flexible and economically driven operation and allocation policies. This optimized operation can be understood as representing operation under a statewide water market or under equivalent economically driven operations. This run was also prepared for CALFED and is extensively documented elsewhere (Jenkins et al., 2001; Draper et al., in press).

- **SWM 2100**: This run extends the SWM 2020 model and concept for 2100 water demands, but retains the same (historical) climate used in Base 2020 and SWM 2020.

- **PCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the dry and warm PCM 2100 climate warming hydrology.

- **HadCM2 2100**: Using the same 2100 water demands as SWM 2100, this run employs the wet and warm HadCM2 2100 climate warming hydrology.

Future performance with climate warming

Population growth will significantly affect the performance and management of California's vast intertied water system. Climate warming could have large additional effects on this system, especially for the agricultural sector of the economy. These effects are summarized in Table ES.3 and Figures ES.3 and ES.4, which contain economic, delivery, and scarcity effects of population growth and climate warming for urban and agricultural water users. Overall, population growth alone raises costs by $4.1 billion/yr, with the driest climate warming hydrology increasing costs a further $1.2 billion/yr. The wet climate warming hydrology decreases total costs by about $0.3 billion/yr. The effects of the driest climate warming scenario are most severe for agricultural users. Given optimized water allocations and operations, water scarcity costs for 2100 without climate changes are less than in 2020 without changes in current water allocation policies. (Most of this difference is attributed to water transfers from Colorado River agricultural users to Southern California urban users.)

Table ES.3. Summary of statewide operating[a] and scarcity costs

Cost	Base 2020	SWM 2020	SWM 2100[b]	PCM 2100[b]	HadCM2 2100[b]
Urban scarcity costs	1,564	170	785	872	782
Agricultural scarcity costs	32	29	198	1,774	180
Operating costs	2,581	2,580	5,918	6,065	5,681
Total costs	**4,176**	**2,780**	**6,902**	**8,711**	**6,643**

a. Operating costs include pumping, treatment, urban water quality, recharge, reuse, desalination, and other variable operating costs for the system. Scarcity costs represent how much users would be willing to pay for desired levels of water delivery.

b. Agricultural scarcity costs are somewhat overestimated because about 2 MAF/yr of reductions in Central Valley agricultural water demands resulting from the urbanization of agricultural land are not included.

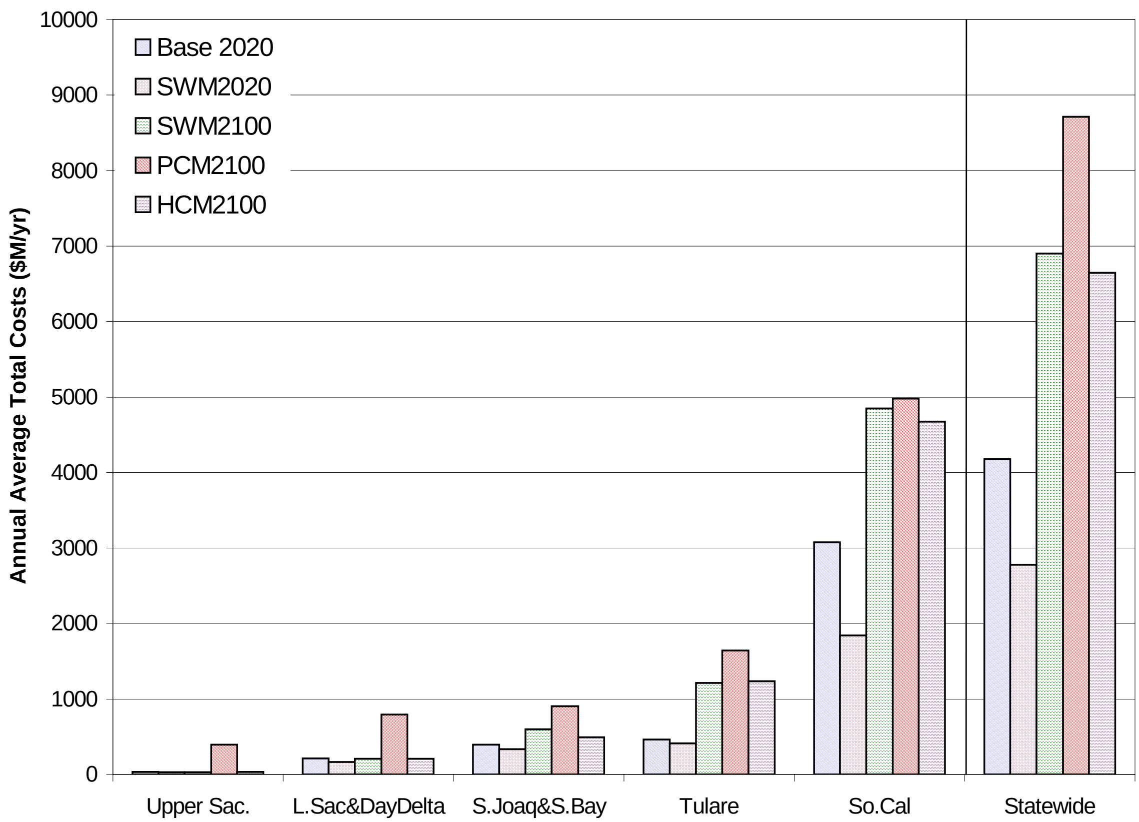

Figure ES.3. Total scarcity and operating costs by region and statewide.

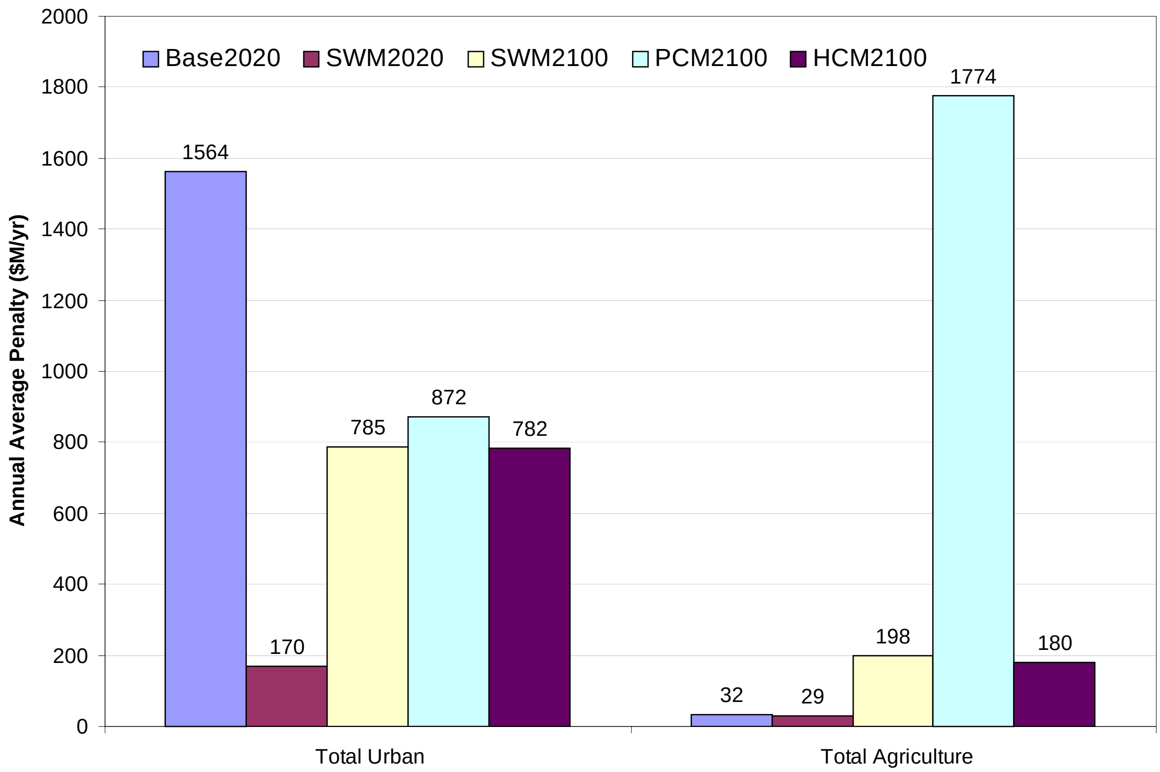

Figure ES.4. Average annual economic scarcity cost by sector.

Hydropower production from the major water supply reservoirs in the California system would not be greatly affected by population growth, but would be reduced by the PCM 2100 climate warming scenario. Base 2020 hydropower revenues average $161 million/yr from the major water supply reservoirs, compared with $163 million/yr for SWM 2100. However, the dry PCM 2100 scenario reduces hydropower revenue 30% to $112 million/yr. Although this does not include the hydropower impacts of climate change on other hydropower plants in California, the reduction percentage is probably reasonable overall. With the wet HadCM2 2100 hydrology, hydropower production greatly exceeds current levels ($248 million/yr).

CALVIN model results indicate several promising and capable adaptations to population growth and climate change (see Figures ES.5 and ES.6). All 2100 scenarios show increased market water transfers from agricultural to urban users, additional urban water conservation (~1 MAF/yr), use of newer water reuse treatment (~1.5 MAF/yr) and sea water desalination technologies (~0.2 MAF/yr), increased conjunctive use of ground and surface waters, and

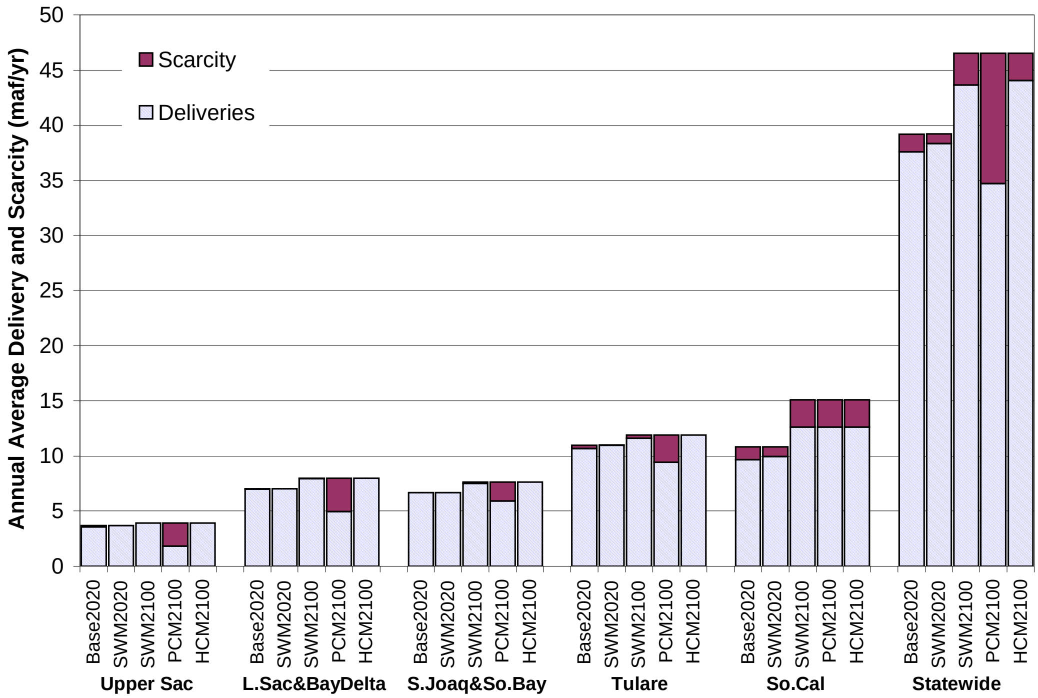

Figure ES.5. Total water deliveries and scarcities by region and statewide.

urbanization of agricultural land. For the dry PCM 2100 scenario, several million acre-feet per year of reductions in agricultural use resulting from land fallowing occur. All of these indicate a much more tightly managed (and controversial) California water system, where water is increasingly valuable because water and the capacities for conveying it are increasingly scarce. The costs of growth and climate change can be large locally and are comparable to the revenues of today's largest water district ($900 million/yr), but are small compared with the size of California's economy (currently $1.3 trillion/yr) or state budget (~$100 billion/yr).

Some operational results for overall surface and groundwater storage in California appear in Figures ES.7 and ES.8. As we can see in these figures, the model operates using a 72-year sequence of inflows based on the historical record to represent hydrologic variability and various complex expressions of wet and dry years, which is quite important for actual operations and water allocations, and for evaluating system performance. Most storage available and used in California is underground. The figures show that more than two-thirds of the storage used between wet and dry periods takes the form of groundwater. The PCM 2100 scenario provides noticeably more challenge for the surface water system overall. All optimized and future scenarios make greater use of groundwater storage for drought management than current policies (Base 2020).

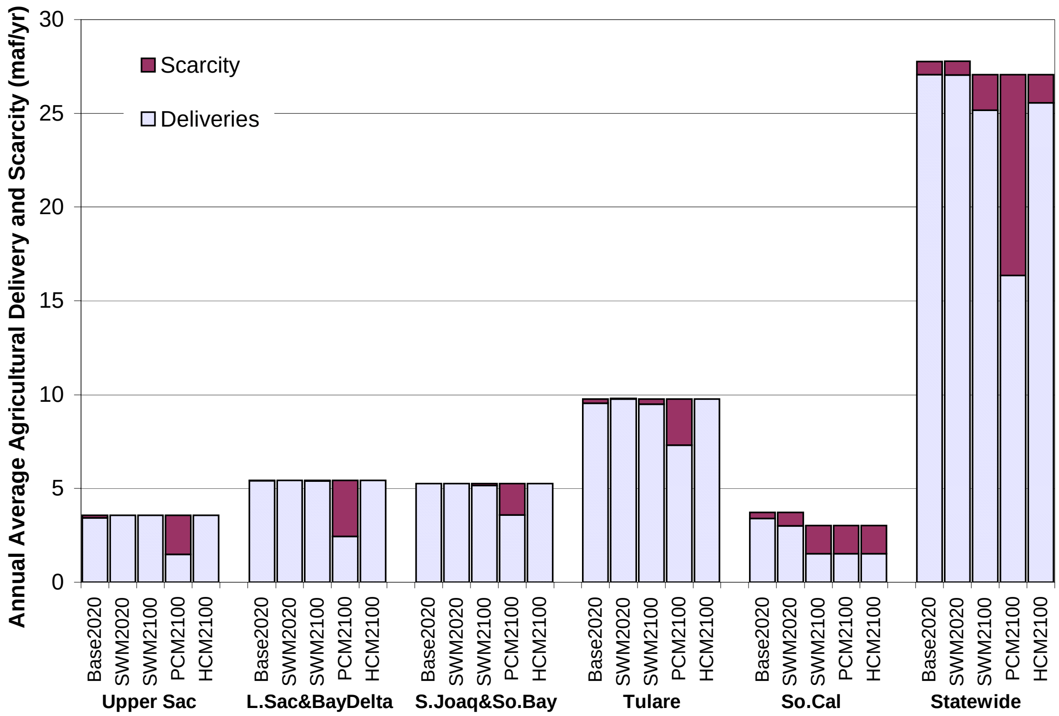

Figure ES.6. Agricultural water deliveries and scarcity by region and statewide.

Population growth and climate warming also pose serious environmental challenges. Although in 2020 (and with 2100 population growth alone), it appears possible to comply with environmental flow and delivery requirements, some small reductions in environmental flows are required for the PCM 2100 scenario. However, increased water demands and decreased water availability do substantially raise the costs of environmental requirements to urban, agricultural, and hydropower users, as shown in Table ES.4. Increased economic costs of complying with environmental requirements could raise incentives to dispute and evade such requirements, as well as incentives to creatively address environmental demands.

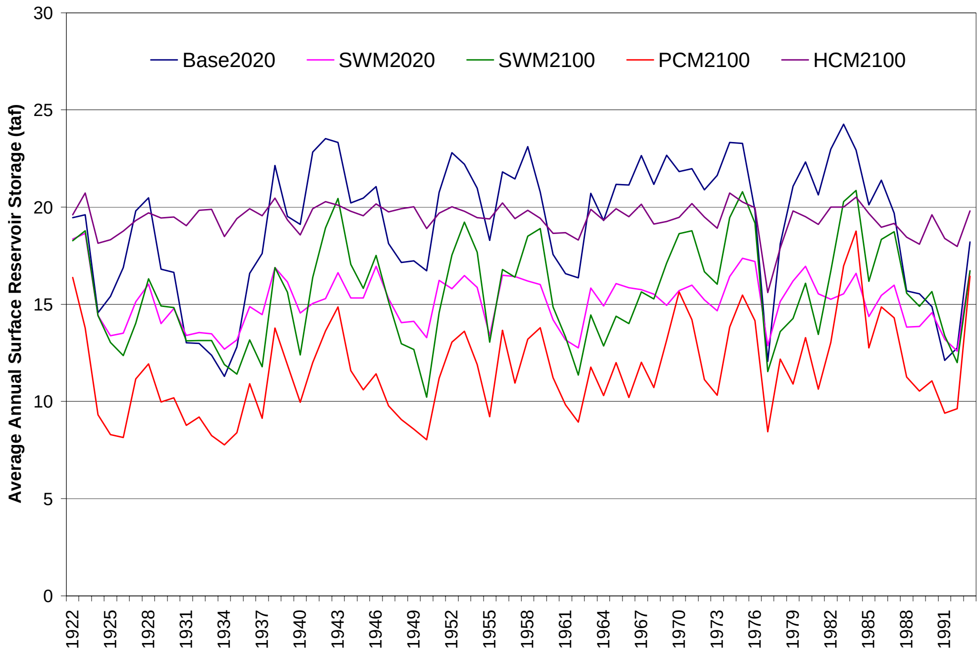

Figure ES.7. Statewide surface water storage over 72-year period.

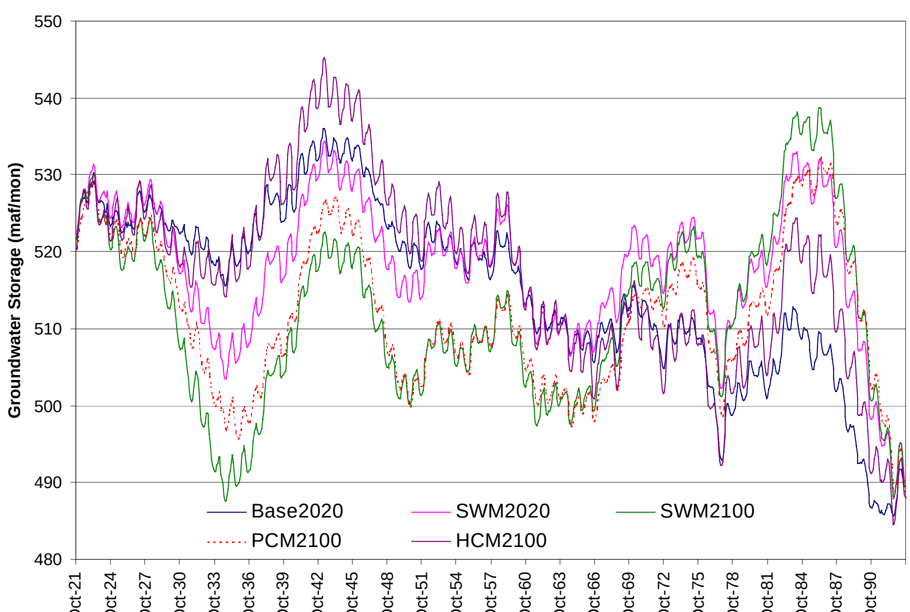

Figure ES.8. Groundwater storage over the 72-year period.

Table ES.4. Shadow costs of selected environmental requirements[a]

	Average willingness to pay ($/acre-ft)			
Minimum instream flows	**SWM 2020[b]**	**SWM 2100**	**PCM 2100**	**HadCM2 2100**
Trinity River	0.6	45.4	1010.9	28.9
Clear Creek	0.4	18.7	692.0	15.1
Sacramento River	0.2	1.2	25.3	0.0
Sacramento River at Keswick	0.1	3.9	665.2	3.2
Feather River	0.1	1.6	35.5	0.5
American River	0.0	4.1	42.3	1.0
Mokelumne River	0.1	20.7	332.0	0.0
Calaveras River	0.0	0.0	0.0	0.0
Yuba River	0.0	0.0	1.6	1.0
Stanislaus River	1.1	6.1	64.1	0.0
Tuolumne River	0.5	5.6	55.4	0.0
Merced River	0.7	16.9	70.0	1.2
Mono Lake inflows	819.0	1254.5	1301.0	63.9
Owens Lake dust mitigation	610.4	1019.1	1046.1	2.5
Refuges				
Sacramento West Refuge	0.3	11.1	231.0	0.1
Sacramento East Refuge	0.1	0.8	4.4	0.5
Volta Refuges	18.6	38.2	310.9	20.6
San Joaquin/Mendota refuges	14.7	32.6	249.7	10.6
Pixley	24.8	50.6	339.5	12.3
Kern	33.4	57.0	376.9	35.9
Delta outflow	0.1	9.7	228.9	0.0

a. Shadow costs are the cost to the economic values of the system (urban, agricultural, hydropower, and operations) of a unit change in a constraint — in this case, environmental flow requirements.

b. SWM 2100 results do not include hydropower values (except for Mono and Owens flows).

Conclusions

We drew a number of conclusions from this work:

- Methodologically, it is possible, reasonable, and desirable to include a wider range of hydrologic effects, changes in population and water demands, and changes in system operations in impact and adaptation studies of climate change than has been customary. Overall, including such aspects in climate change studies yields more useful and realistic results for policy, planning, and public education purposes.

- A wide range of climate warming scenarios for California shows significant increases in wet season flows and significant decreases in spring snowmelt. This conclusion, which confirms many earlier studies, is made more generally and quantitatively for California’s major water sources. The magnitude of climate warming’s effect on water supplies can be comparable to water demand increases from population growth in the coming century.

- California’s water system can adapt to the population growth and climate warming scenarios that were modeled, which are fairly severe. This adaptation will be costly in absolute terms, but, if properly managed, should not threaten the fundamental prosperity of California’s economy or society (although it can have major effects on the agricultural sector). The water management costs are a tiny proportion of California’s current economy.

- Agricultural water users in the Central Valley are the most vulnerable to climate warming. Wetter hydrologies could increase water availability for these users, but the driest climate warming hydrology would reduce agricultural water deliveries in the Central Valley by about one-third. Some losses to the agricultural community in the dry scenario would be compensated by water sales to urban areas, but much of this loss would be an uncompensated structural change in the agricultural sector.

- Water use in Southern California is likely to become predominantly urban in this century, with Colorado River agricultural water use being displaced by urban growth and diverted to serve urban uses. This diversion is limited only by conveyance capacity constraints on the Colorado River Aqueduct deliveries of Colorado River water and California Aqueduct deliveries of water from the Central Valley. Given the small proportion of local supplies in southern California, the high willingness to pay of urban users for water, and the conveyance-limited nature of water imports, this region would be little affected by climate warming. Indeed, even in the dry scenario, Southern California cannot seek additional water imports. Population growth, conveyance limits on imports, and high economic values lead to high levels of wastewater reuse and lesser but substantial use of sea water desalination along the coast.

- Flooding problems could be formidable under some wet warming climate scenarios. Flood flows indicated by the HadCM2 2100 scenario would be well beyond the control capability of existing, proposed, and probably even plausible reservoir capacities. In such cases, major expansions of downstream floodways and changes in floodplain land uses might become desirable.

- Although adaptation can be successful overall, the challenges of population growth and climate warming are formidable. Even with new technologies for water supply and treatment, increased water use efficiency, widespread implementation of water transfers and conjunctive use, coordinated operation of reservoirs, improved flow forecasting, and the close cooperation of local, regional, state, and federal governments, the costs will be high and there will be much less "slack" in the system compared to current operations and expectations. Even with historical hydrology and continued population growth, the economic implications of water management controversies will be greater, motivating greater intensity in water conflicts, unless management institutions can devise more efficient and flexible mechanisms and configurations for managing water in the coming century.

- The limitations of this kind of study are considerable, but the qualitative implications seem clear. It behooves us to carefully consider and develop a variety of promising infrastructure, management, and governance options to allow California and other regions to respond more effectively to major challenges of all sorts in the future.

Further climate change work on water in California should be expanded from this base to include flood damage costs, sea level rise, other forms of climate change (such as various forms of climate variability), some refinements in hydrologic representation, and some operations model improvements discussed in this appendix. Other general improvements in the CALVIN model, particularly representations of the Tulare Basin, Central Valley groundwater, and agricultural water demands are also desirable.

1. Introduction

The earth's climate has changed over the course of history and prehistory and shows prospects of continuing to change (Lamb, 1982). Climate appears to change in various ways. Some changes appear to us as variability in climate, seeming to oscillate over periods of several years or perhaps decades (Trewartha, 1954; Cayan et al., 1999). Other changes are more long term, occurring over many decades. These long-term changes can take the forms of climate warming, sea level rise, or other such phenomena.

Any long-term changes in climate will have implications for how water is managed, as well as for many other aspects of our society, economy, and environmental resources. However, in the future when we must manage such changes in climate, other significant changes will be taking place in our society and economy, not the least of which will be population growth and accompanying changes in land use and economic structure. The relative roles and importance of such different uncertainties in the design of future water systems is a common topic of professional discussion. In these discussions, climate change is often judged to be less important than other aspects of the future (Rogers, 1993; Klemes, 2000a, 2000b). At a global scale, Vörösmarty et al. (2000) find that population growth overshadows climate change as a driver of future water problems. Others point out the great adaptive capacity of water resource systems and the societies and economies they serve, particularly over long periods of time (Stakhiv, 1998). In this appendix, we are concerned with climate change's role in the future of California water management, a future that will be different from today's reality, even without climate change.

In California, concern for climate change has increased recently as research on global climate change has been applied to the state and as it has become apparent that California's climate has changed significantly in recent times (Dettinger and Cayan, 1995; Roos, 2002; Lower American River flood frequencies) and over recent millennia (Stine, 1994). Several decades of studies have shown that California's climate is variable over history and in the present (Cayan et al., 1999), is experiencing continuing sea level rise (Logan, 1990), and may experience significant climate warming (Lettenmaier and Gan, 1990; Gleick and Chalecki, 1999).

Many studies on climate changes and their potential wide-ranging effects on California exist, and they have been nicely reviewed by Gleick and Chalecki (1999) and Wilkinson (2002). Among the direct hydrologic effects are:

- sea level rise, affecting coastal areas somewhat, but mostly affecting flooding and water quality in the Sacramento-San Joaquin Delta
- increased mountain runoff in winter months and reductions of spring runoff, resulting from diminished storage in mountain snowpacks, which worsens winter flood problems and makes it more difficult to capture and store large quantities of wet season runoff for dry season water supplies
- statewide increases in evaporation rates caused by higher temperatures
- increases, or perhaps decreases, in precipitation, which raise or reduce annual runoff volumes
- potential changes in the duration and severity of droughts or floods, or both.

This study focuses on the effects of a range of climate warming estimates on the long-term performance and management of California's water system. This is a complex and somewhat speculative business, because so much can change in the long term. For this reason, it makes little sense to look at an individual change without placing that change in the context of other likely changes and looking at reasonable adaptations that our society and economy would make to future changes in climate. In our preliminary integrated analysis of how California could respond to climate change, then, we examine adaptive responses to climate warming in the context of increased population, continued conversion of agricultural land to urban uses, and changes in crop yields resulting from climate change and sustained technological improvements in agriculture.

This appendix is organized as follows. Section 2 presents climate warming scenarios that can be reasonably expected for California and discusses how these climate changes were transformed into detailed, spatially distributed surface and groundwater hydrologies for the state's water supply system for 2100. This represents the first comprehensive quantification of the implications of climate change for the various water sources that supply California's extensive and highly diversified system. Section 3 considers nonclimate changes that can be reasonably expected in 2100, providing a more realistic context for assessing the implications of climate change in the distant future. Changes in population, land use, and technology are discussed, and reasonable quantitative characterizations are made for 2100, although these are not the only reasonable characterizations of the future. Section 4 presents the various options that are available to help the state adapt to future changes in water supplies and demands. These adaptations include changes in facilities, demands, allocations, and water management institutions. Section 5 describes this study's analytical approach, in which climate and nonclimate changes were used to modify a quantitative understanding of California's integrated water management system in the form of the CALVIN model. Results from this model are also given in Section 5. Section 6 examines these results in terms of the economic and adaptation implications of climate and other changes for California's very long-term water supplies (and demands).

Several attachments accompany this appendix, sparing the reader the gorier details of this work but making these details available for fellow water wonks. Attachment A presents the details of how comprehensive climate warming hydrologies were developed. Attachment B contains details of urban water demand estimation and estimates for 2100, and Attachment C does the same for estimation of agricultural water demands for 2100. Hydropower valuation, a newly added feature for the CALVIN model, appears in Attachment D. Attachment E contains a revision of environmental water constraints in the CALVIN model also developed as part of this project.

This section summarizes the more complete review of climate change and climate change hydrologies appropriate for water supply studies in California that makes up Attachment A. We begin the section with brief discussions of historical and prehistoric experiences with climate change and prospects for future climate changes, and conclude with a summary of the method and results of statewide estimates for 12 climate change scenarios for California.

1.1 Past Climate Changes

In terms of runoff and temperature, there is historical and prehistorical evidence of great consistency in California's climate, as well as great variability during the last few thousand years. Streamflow records dating from about 1900 and estimated streamflows from tree-ring studies going back to about 900 A.D. generally indicate similar annual variability in streamflows (Meko et al., 2001). However, other detailed studies of the state's climate give indications of prolonged drier periods before European settlement. Stine (1996) argues that the period from 1650 to 1850 was significantly drier and cooler than the current era, with perhaps 23%-24% less runoff annually, and that this dry cool period was anomalous for this post-ice-age period overall (the past 8,000 years). Although these studies are unable to indicate the seasonality of flows, a cooler climate would generally delay snowmelt, with a greater proportion of flows occurring in spring and summer. Stine also contends that extreme and prolonged droughts, related to large-scale global climate fluctuations, have occurred in California. Haston and Michaelsen (1997) also find long-term spatial and temporal variability in California's climate related to global-scale atmospheric circulation patterns.

Sea level is another important aspect of climate change that affects water management in California. The level of the sea has a significant effect on coastal wetlands and ecology, as well as on salinity levels in the San Francisco Bay-Delta estuary, with its environmental, economic, and water supply importance. It is generally thought that sea level has risen over the past few thousand years. Estimates of the rate of rise in sea level range from 0.1 m to 0.9 m/century (Intergovernmental Panel on Climate Change [IPCC], 2001; Roos, 2002).

1.2 Future Climate Changes

Although a variety of changes in California's climate have been seen in historical and prehistorical periods or could occur in the future, three forms of climate change are most frequently discussed for California's future (Roos, 2002; Wilkinson, 2002): sea level rise, climate variability, and climate warming.

1.2.1 Sea level rise

Sea level rise is probably the most certain and predicable climate change occurring in California, and perhaps the most important aspect of sea level rise for the state's water supply system is its likely effects on the Sacramento-San Joaquin Delta (Logan, 1990; Anderson, 2002). The delta estuary is a central hub of California's water system, with a degree of mixing of sea water and fresh water as water is pumped from the delta for export to most of California's agricultural and urban activity centers. The delta itself is also a major agricultural production area as well as a key environmental habitat and recreation area. Expected levels of sea level rise are likely to amplify already problematic risks of flooding in this region (Williams, 1989; Logan, 1990) and increase the salinity of water at major export pumping locations unless addressed with changes in delta outflows, channels, or operations. Increased exports of sea salts from the delta would increase salt disposal problems in the San Joaquin and Tulare basins. The increased presence of disinfection by-product precursors (particularly bromides) from sea water would also raise health risks or water treatment costs for urban water users in much of the state (Hutton and Chung, 1992; Anderson, 2002).

1.2.2 Climate variability

Variability in climate refers to changes in the persistence and frequency of wet and dry periods over time. Do droughts become more frequent and severe? Are floods more frequent, or less so? Variability of climate has long been known to exist (Trewartha, 1954). Recent works have shown several global and regional circulation mechanisms that can drive the variability of California's climate, the now well-known El Niño and Pacific Decadal Oscillation events (Haston and Michaelsen, 1997; Cayan et al., 1999, Biondi et al., 2001).

One of the more interesting aspects of research into climate variability is the prospect it might offer for better weather and climate prediction (Masutani and Leetmaa, 1999). If droughts and floods can be better predicted, it should be possible to operate water resource systems with greater foresight. For example, if floods can be predicted meteorologically and climatologically, more water could be captured and carried over during the winter months to increase water supplies. If droughts can be better predicted, it should be possible to begin water conservation efforts earlier to better conserve water supplies during droughts and perhaps draw down reserves with greater confidence of a drought's end (Carpenter and Georgakakos, 2001; Yao and Georgakakos, 2001).

1.2.3 Climate warming

Perhaps the most-debated form of climate change for California is climate warming, usually attributed to increasing concentrations of carbon dioxide and other gases from increased industrialization over the last century (Wigley and Raper, 2001; Snyder et al., 2002). Many studies have explored the potential effects of climate warming on streamflows in California (Lettenmaier and Gan, 1990; Lettenmaier and Sheer, 1991; Cayan et al., 1993; Gleick and Chalecki, 1999; Miller et al., 2001; Roos, 2002). The degree of warming is usually estimated based on the results of computer models of the Earth's climate, known as general circulation models (GCMs). These studies all indicate that warming of California's climate would change the seasonal distribution of runoff, with a greater proportion of runoff occurring during the wet winter months, and less snowmelt runoff seen during the spring months. Some sets of GCM results indicate that higher precipitation volumes are likely to accompany any climate warming, arising in part from higher global evaporation rates. There is some reason to think that seasonal shifts in runoff patterns from spring to winter are already occurring in California (Aguado et al., 1992; Dettinger and Cayan, 1995). Changes in the persistence of wet and dry periods with climate warming are only beginning to be explored (Huber and Caballero, 2003).

1.3 Twelve Climate Change Scenarios

This study examines the effects of a range of climate warming scenarios on the long-term performance and management of California's water system.

1.3.1 Twelve views of future California climate with global warming

To represent the range of climate warming likely to be experienced in California in the coming century, we used 12 climate change scenarios. Six of these scenarios are taken from two major GCM studies, the generally much wetter and warmer HadCM2 model and the much drier and warmer PCM model. For each GCM, we examined three periods into the future: 2010-2039, 2050-2079, and 2080-2099. In addition, six parametric changes were explored for California, with temperature increases ranging from 1.5°C to 5.0°C and precipitation increases from 0% to 30%.

The 12 climate change scenarios examined are

1. 1.5°C temperature increase and 0% precipitation increase (1.5 T 0% P)
2. 1.5°C temperature increase and 9% precipitation increase (1.5 T 9% P)
3. 3.0°C temperature increase and 0% precipitation increase (3.0 T 0% P)
4. 3.0°C temperature increase and 18% precipitation increase (3.0 T 18% P)
5. 5.0°C temperature increase and 0% precipitation increase (5.0 T 0% P)

6. 5.0°C temperature increase and 30% precipitation increase (5.0 T 30% P)
7. HadCM2 2010-2039
8. HadCM2 2050-2079
9. HadCM2 2080-2099
10. PCM 2010-2039
11. PCM 2050-2079
12. PCM 2080-2099.

These climate change scenarios represent a range of results found from a wide variety of GCM outcomes, as shown in Figure 1 and Table 1.

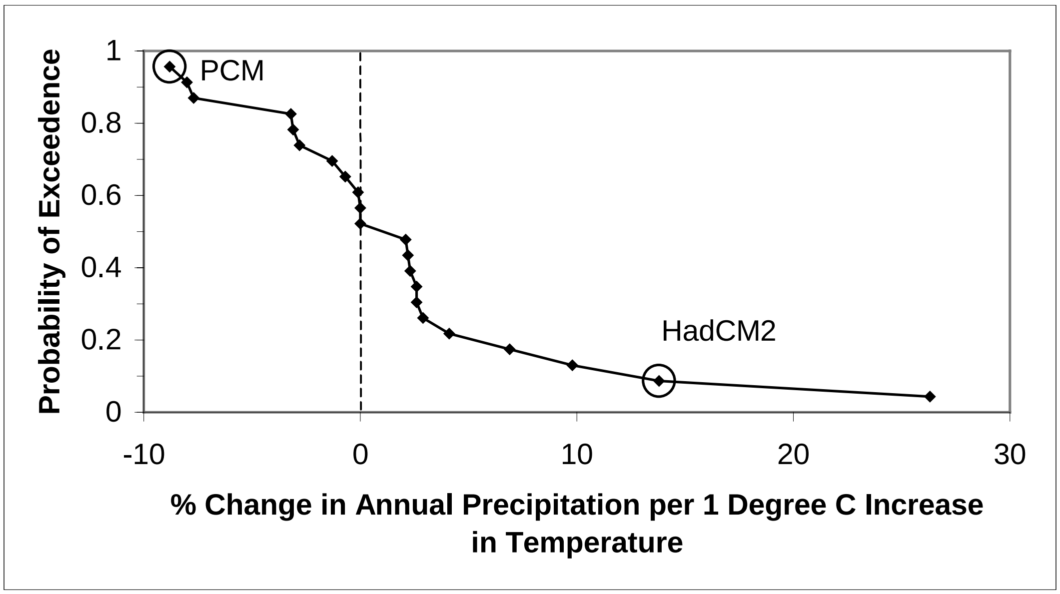

Figure 1. Probability of precipitation effect of temperature rise from data in Table 1.

Table 1. Average precipitation changes for California grid cells (percent change per 1°C global-mean warming)

	Annual	December-February	June-August
BMRC	-8.0	-6.5	-9.9
CCC	6.9	14.0	3.5
CSIR1	-0.7	-1.8	-1.0
CSIR2	2.6	5.3	-2.7
ECH1	9.8	8.4	2.8
ECH3	-3.2	9.9	-22.5
GFDL	0.0	1.8	-0.1
GISS	2.2	1.5	3.6
LLNL	0.0	1.5	-2.7
OSU	-1.3	0.6	-5.2
UIUC	2.3	0.3	34.7
UKHI	2.6	6.2	-5.2
UKLO	4.1	6.1	-0.2
UKTR	2.9	12.4	0.3
CCCTR	26.3	56.0	7.1
JAPAN	-7.7	-10.7	0.7
CSITR	-2.8	7.7	-10.0
ECH4	-3.1	8.7	-8.1
GFDTR	-0.1	-3.4	-4.6
NCAR	2.1	0.4	7.4
HadCM2	13.8	23.1	7.8
PCM	-8.8	-	-
Overall mean	**1.8**	**6.7**	**-0.2**
Median	**1.05**	**5.3**	**-0.2**
Maximum	**26.3**	**56.0**	**34.7**
Minimum	**-8.8**	**-10.7**	**-22.5**

Notes:
Grid box central points (5° by 5° grid).
Latitude range 32.5 to 42.5 N.
Longitude range -122.5 to -117.5 E.
Sources: Tom M.L. Wigley, National Center for Atmospheric Research (NCAR), personal communication.
PCM added June 21, 2000, based on changes in precipitation and temperature for California from Miller et al., 2001.

1.3.2 Components of California's water supply

The water supply to the state's water system can be divided into several components:

- **Mountain rim inflows**, which supply 72% (28.2 MAF/yr) of inflows to California's intertied water system, come from mountain rainfall and snowmelt. When they enter the rims of California's Central Valley floor, they are often intercepted by sizable storage reservoirs, which help to control floods, as well as the seasonal distribution of water to support agriculture and urban uses.

- **Local accretions to surface water**, which represent about 11% (4.4 MAF/yr) of inflows to the system, arrive directly from rainfall on the Central Valley and local stream runoff.

- **Groundwater recharge from rainfall**, which make up about 17% (6.8 MAF/yr) of inflows, accounts for the rainfall on the Central Valley that does not run off or evaporate during wet seasons.

- **Reservoir evaporation,** which is a loss the system pays for storing water in surface reservoirs. Currently, reservoir evaporation amounts to about 4% (1.6 MAF/yr) of annual inflow to the system.

In this work, we estimated changes in all these system components for each of the 12 climate warming scenarios for the entire state water supply system.

Hydrologic modeling for six index basins

Estimates of changes in rim inflows were based on detailed studies conducted by Lawrence Berkeley National Laboratory (LBNL) of six index basins distributed throughout California (Miller et al., 2001). These basins, shown in Figure 2, represent a range of snowmelt- and rainfall-dominated catchments. Each of the 12 scenarios was used to drive standard rainfall-runoff models for each of these six basins, based on existing National Weather Service (NWS) rainfall-runoff models of these basins. We examined the results from these model runs for internal consistency and consistency across basins.

Development of statewide surface and groundwater hydrologies

As described in detail in Attachment A, we used the results of six index basins to develop rim inflows for each of 37 major surface inflows to California's water supply system. Streamflow changes for each of the six index basins were then mapped to the 37 major surface inflows to the system, perturbing the 72-year historical flow record to represent historical spatial and temporal variability of inflows given a generally warmer (and for some scenarios wetter or drier) climate. Next, we employed the climate used for each climate warming scenario model run to estimate

Figure 2. Location of the six index basins (Miller et al., 2001).

changes in flows for mountain rim inflows, local runoff, rain-fed deep percolation to groundwater, and reservoir evaporation. These results of these analyses appear below, with more detail to be found in Attachment A. Figure 3 shows the variety of surface, groundwater, reservoir evaporation, and local inflow locations.

Mountain rim runoff results

Table 2 presents the rim inflow quantities and changes for the 12 scenarios. For most cases, overall inflows into the system are greater with climate warming, driven by accompanying precipitation increases. Only for the three very dry PCM runs and the high temperature with low precipitation scenario did overall rim inflow decrease. However, any increases in annual runoff occurred only during the wet winter months (October through March), the only exception being the very wet HadCM2 GCM results. The general impression of these results confirms widespread concerns that climate warming would worsen California's already skewed seasonal hydrology, making wet winters wetter and more flood-prone, and reducing runoff during the snowmelt portion of the dry season. Figure 4 shows these results graphically.

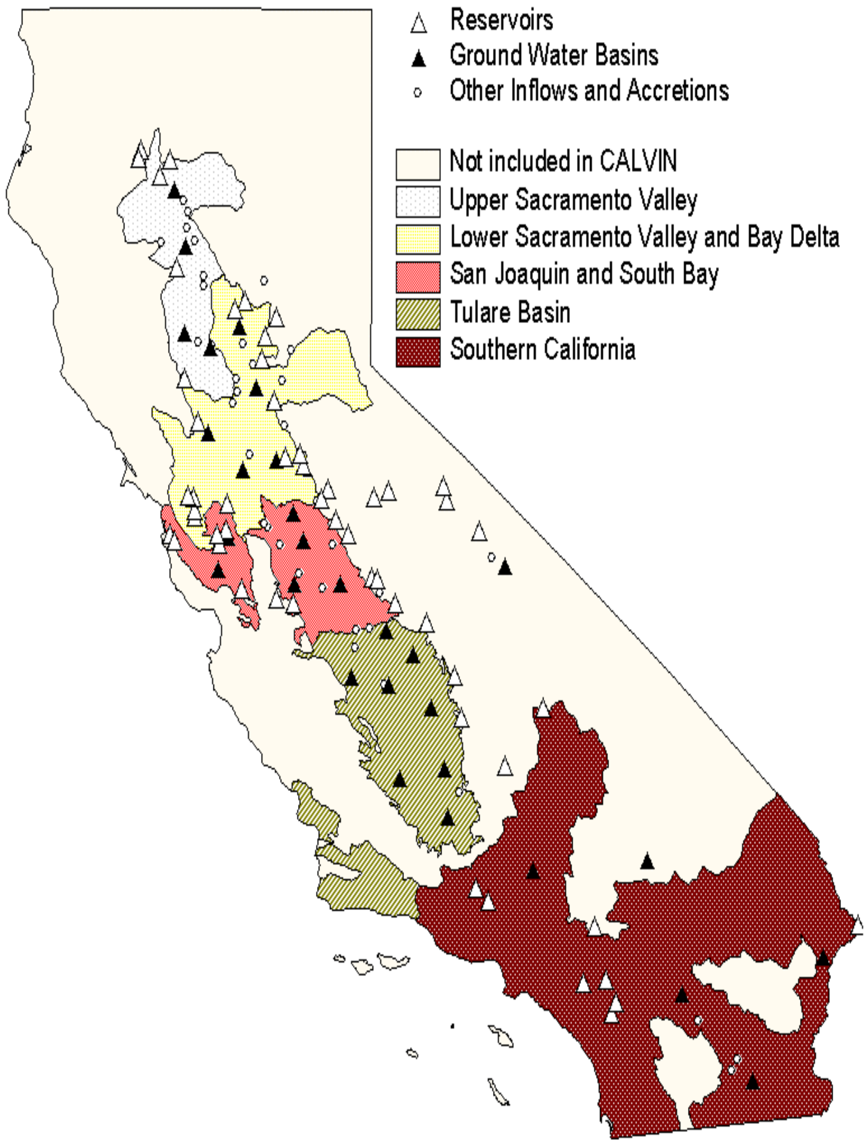

Figure 3. CALVIN model regions, inflows, and reservoirs.

Table 2. Overall rim inflow quantities and changes

Climate scenario	Annual Quantity (MAF)	Annual Change (%)	October-March Quantity (MAF)	October-March Change (%)	April-September Quantity (MAF)	April-September Change (%)
1. 1.5 T 0% P	28.6	1.1	16.4	15.6	12.2	-13.4
2. 1.5 T 9% P	32.4	14.6	18.7	31.7	13.7	-2.7
3. 3.0 T 0% P	28.5	0.9	18.2	28.0	10.3	-26.5
4. 3.0 T 18% P	36.2	28.1	23.3	64.4	12.8	-8.7
5. 5.0 T 0% P	27.9	-1.1	19.5	37.1	8.5	-39.7
6. 5.0 T 30% P	40.6	43.7	28.9	103.8	11.7	-17.0
7. HadCM2 2010-2039	38.5	36.4	22.0	54.9	16.5	17.6
8. HadCM2 2050-2079	41.3	46.4	25.8	82.0	15.5	10.4
9. HadCM2 2080-2099	49.8	76.5	33.3	134.3	16.6	18.1
10. PCM 2010-2039	26.5	-6.2	13.2	-6.7	13.2	-5.7
11. PCM 2050-2079	24.4	-13.6	13.7	-3.8	10.7	-23.5
12. PCM 2080-2099	21.1	-25.5	12.2	-14.2	8.9	-36.9
Historical	28.2	0.0	14.2	0.0	14.0	0.0

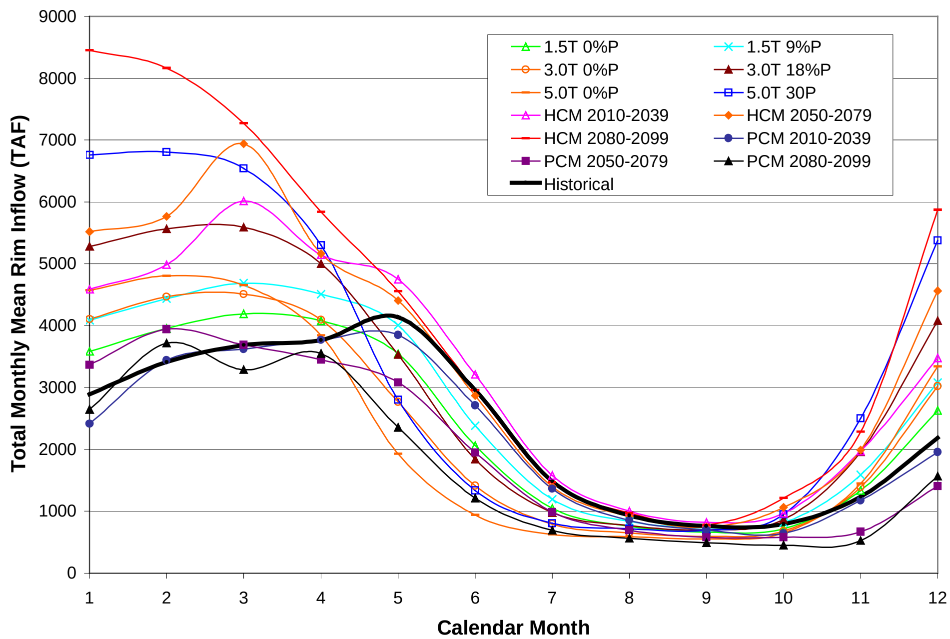

Figure 4. Seventy-two year period monthly mean rim inflows for the 12 climate scenarios and historical data.

The classical concern for climate warming in California and throughout the West is that increased winter flooding and decreased snowmelt would pose a double threat to water supplies from surface reservoirs in mountain foothills (Lettenmaier and Gan, 1990). Such reservoirs would have to maintain greater empty space to maintain current levels of flood protection from increased winter storm runoff. This empty space would then be less likely to refill at the end of the flooding season because of reductions in snowmelt after the storm season's end. Estimated implications for overall water supply reliability are discussed later in this chapter, without the benefit of operations model results. Results of operations model refinements are given in Section 5.

Local runoff results

Local valley runoff changes with climate warming are estimated from precipitation change assumptions for the six parametric scenarios and the six GCM scenarios. These results for the 38 local runoff inflows are given in Table 3. Except for the PCM, these results are more benign for water supply, with general increases or no effect on dry season runoff, but frequent substantial increases in winter runoff. The volumetric flow changes are much less for local runoff than for rim flows, however.

Table 3. Local surface water accretion quantities and changes

	Annual		October-March		April-September	
Climate scenario	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)
1. 1.5 T 0% P	4.42	0.0	3.54	0.0	0.88	0.0
2. 1.5 T 9% P	5.45	23.3	4.39	23.9	1.06	21.1
3. 3.0 T 0% P	4.42	0.0	3.54	0.0	0.88	0.0
4. 3.0 T 18% P	6.48	46.6	5.23	47.7	1.25	42.1
5. 5.0 T 0% P	4.42	0.0	3.54	0.0	0.88	0.0
6. 5.0 T 30% P	7.85	77.7	6.36	79.5	1.49	70.2
7. HadCM2 2010-2039	7.94	79.7	6.04	70.4	1.91	117.4
8. HadCM2 2050-2079	8.55	93.4	7.04	98.7	1.51	72.0
9. HadCM2 2080-2099	11.41	158.1	9.72	174.3	1.69	92.8
10. PCM 2010-2039	4.26	-3.5	3.23	-8.8	1.03	18.0
11. PCM 2050-2079	3.89	-12.0	3.08	-12.9	0.81	-8.2
12. PCM 2080-2099	3.17	-28.2	2.36	-33.2	0.81	-7.8
Historical	4.42	0.0	3.54	0.0	0.88	0.0

Deep percolation to groundwater results

Like local valley runoff, deep percolation to groundwater from precipitation is estimated based on precipitation changes for each climate warming scenario, using methods described in Attachment A. Table 4 summarizes these results for CALVIN's 28 groundwater basins. Except for the dry PCM, annual groundwater availability increases for the climate warming scenarios. Even with the dry PCM precipitation, reductions in groundwater availability are small.

Groundwater inflow changes differ from rim inflow changes. Additional groundwater inflows during the wet season are stored and become available for use during the dry season. We will explore the water supply implications, which become an essential part of the operations model results, later in this appendix. Groundwater, already a significant part of California's water supply system, would somewhat mitigate the larger water supply impacts of climate warming on rim inflows.

Table 4. Groundwater inflow quantities and changes

	Annual		October-March		April-September	
Climate scenario	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**
1. 1.5 T 0% P	6.78	0.0	3.60	0.0	3.18	0.0
2. 1.5 T 9% P	7.01	3.4	3.80	5.5	3.21	1.0
3. 3.0 T 0% P	6.78	0.0	3.60	0.0	3.18	0.0
4. 3.0 T 18% P	7.24	6.8	4.00	11.1	3.24	1.9
5. 5.0 T 0% P	6.78	0.0	3.60	0.0	3.18	0.0
6. 5.0 T 30% P	7.55	11.3	4.27	18.5	3.28	3.2
7. HadCM2 2010-2039	7.51	10.7	4.17	15.8	3.33	5.0
8. HadCM2 2050-2079	7.68	13.3	4.42	22.7	3.26	2.5
9. HadCM2 2080-2099	8.37	23.5	5.08	41.1	3.29	3.5
10. PCM 2010-2039	6.61	-2.5	3.42	-5.0	3.19	0.3
11. PCM 2050-2079	6.44	-5.0	3.33	-7.6	3.11	-2.0
12. PCM 2080-2099	6.21	-8.5	3.08	-14.5	3.12	-1.7
Historical	6.78	0.0	3.60	0.0	3.18	0.0

Reservoir evaporation results

Table 5 presents the results for the 47 surface reservoirs in our representation of California's intertied water system. Substantial increases in reservoir evaporation occur for all climate warming scenarios.

Total water quantity changes

The summed changes in water quantities from changes in rim, valley floor, and groundwater inflows, as well as in reservoir evaporation, appear in Table 6. They indicate a wide range, positive and negative, of potential overall changes in annual water inflows to California's system. However, there is consistency in the seasonal shift in inflows, with less spring snowmelt, and typically much greater winter flows. In the next section, we modify these results to crudely estimate overall changes in water supply availability for these scenarios, without detailed operations modeling.

Table 5. Surface reservoir evaporation quantities and changes

	Annual		October-March		April-September	
Climate scenario	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)
1. 1.5 T 0% P	1.83	12.4	0.46	27.0	1.36	8.1
2. 1.5 T 9% P	1.81	11.6	0.45	24.3	1.36	7.9
3. 3.0 T 0% P	2.03	24.8	0.56	54.0	1.46	16.3
4. 3.0 T 18% P	2.00	23.2	0.54	48.5	1.46	15.8
5. 5.0 T 0% P	2.30	41.3	0.70	90.0	1.60	27.1
6. 5.0 T 30% P	2.25	38.6	0.66	80.9	1.59	26.3
7. HadCM2 2010-2039	1.77	9.0	0.43	16.8	1.34	6.7
8. HadCM2 2050-2079	1.90	16.9	0.49	33.3	1.41	12.1
9. HadCM2 2080-2099	1.98	21.7	0.52	40.7	1.46	16.2
10. PCM 2010-2039	1.68	3.6	0.40	8.0	1.29	2.3
11. PCM 2050-2079	1.84	13.5	0.48	30.8	1.37	8.5
12. PCM 2080-2099	1.98	21.6	0.55	49.9	1.43	13.4
Historical	1.62	0.0	0.37	0.0	1.26	0.0

Table 6. Overall water quantities and changes

	Annual		October-March		April-September	
Climate scenario	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**
1. 1.5 T 0% P	37.9	0.3	23.1	10.1	14.9	-11.8
2. 1.5 T 9% P	43.0	13.7	26.4	26.0	16.6	-1.5
3. 3.0 T 0% P	37.7	-0.4	24.8	18.0	12.9	-23.4
4. 3.0 T 18% P	47.9	26.6	32.0	52.7	15.9	-5.9
5. 5.0 T 0% P	36.8	-2.6	25.9	23.6	10.9	-35.1
6. 5.0 T 30% P	53.7	42.1	38.9	85.5	14.8	-11.9
7. HadCM2 2010-2039	52.2	38.0	31.8	51.5	20.4	21.2
8. HadCM2 2050-2079	55.7	47.2	36.8	75.5	18.9	12.0
9. HadCM2 2080-2099	67.6	78.9	47.5	126.6	20.1	19.3
10. PCM 2010-2039	35.7	-5.6	19.5	-7.0	16.2	-3.9
11. PCM 2050-2079	32.9	-13.0	19.6	-6.6	13.3	-21.0
12. PCM 2080-2099	28.5	-24.8	17.1	-18.6	11.4	-32.5
Historical (1921-1993)	37.8	0.0	21.0	0.0	16.8	0.0

Changes in water availability

Table 7 contains the estimated changes in overall water availability for water supply purposes as a result of the 12 climate warming scenarios. These changes reflect two crude assumptions — that no increases in winter runoff can be captured (because of the need to operate reservoirs for flood control) and that all reductions in spring and dry season inflows are directly lost for water supplies. However, increases in wet season inflows to groundwater are captured and become available to the water supply. These results are generally more pessimistic than the overall annual estimates in Table 6. The effects of groundwater somewhat reduce the dramatic seasonal changes of rim inflows.

The water quantity losses in Table 7 are sizable for some scenarios and insignificant for others. Under some scenarios, gains are even seen. Plausible water supply impacts of climate warming to California range from a loss of 9.4 MAF/yr to a gain of 4.6 MAF/yr, or a 25% decrease to a 12% increase in water supply availability. All the climate warming scenarios, except for the HadCM2 GCM model results, show losses of water supply ranging from slight to considerable. These are but crude estimates of changes in water supply availability from climate warming, and they might be pessimistic. The ability of California's water management system to adapt to these changes in water availability would generally be expected to improve these effects on water supply availability. Section 5 explores the capacity of California's water management infrastructure to adapt to such climate warming scenarios.

Table 7. Raw water availability estimates and changes (without operational adaptation, in MAF/yr)

	Average annual water availability	
Climate scenario	**Volume (MAF)**	**Change MAF (%)**
1. 1.5 T 0% P	35.7	-2.1 (-5.5%)
2. 1.5 T 9% P	37.7	-0.1 (-0.4%)
3. 3.0 T 0% P	33.7	-4.1 (-10.9%)
4. 3.0 T 18% P	37.1	-0.8 (-2.0%)
5. 5.0 T 0% P	31.6	-6.2 (-16.5%)
6. 5.0 T 30% P	36.2	-1.6 (-4.3%)
7. HadCM2 2010-2039	41.9	4.1 (10.8%)
8. HadCM2 2050-2079	40.5	2.7 (7.2%)
9. HadCM2 2080-2099	42.4	4.6 (12.1%)
10. PCM 2010-2039	35.7	-2.1 (-5.6%)
11. PCM 2050-2079	32.9	-4.9 (-13.0%)
12. PCM 2080-2099	28.5	-9.4 (-24.8%)
Historical	37.8	0.0 (0.0%)

2. Major Nonclimate Changes

A century brings profound changes in most aspects of modern society. In general, throughout each century for the past 1,000 years, population has grown significantly, population demography and composition has changed considerably, wealth has increased substantially, major economic sectors have come and gone, the structure of cities and the routines of daily life have changed, and governmental activities and the role of government have evolved. And as the values of the society develop, language, culture, and art all change appreciably.

Recently, our society has begun to examine the possibility of climate changing over such time frames. Vörösmarty et al. (2000) examined the comparative roles of global population and climate changes, finding that population growth responds to climate change in important ways. However California's climate changes over the coming century, the way Californians respond and are affected by climate change will be driven largely by the fundamental nonclimate changes that characterize the state's society and economy.

This section presents plausible quantitative projections or speculations of some major nonclimate changes that could reasonably be expected in the coming century. Such speculations are unavoidably subject to errors and critical commentary, for just as no one can know detailed weather on some distant day, no one can know details of the climate, population, demography, wealth, transportation modes, government roles, stock market performance, economic structure, or even the music that will be popular in 2100. (Merely knowing that these things will continue to exist in 2100 would relieve many of us considerably.) Nevertheless, given the planning and policy lead times often needed to make profound changes in water infrastructure, perhaps 100-year projections are themselves unavoidable to allow us to begin preparing ourselves.

2.1 Population and Urban Water Demands

"In the long run, we will all be dead."

— John Maynard Keynes

As individuals, yes, we will all be dead in the long run. However, as a society and a population, there probably will be many more of us in California in the future. The state has experienced a steady and at times explosive growth for more than 100 years, and the climate, economic incentives, and cultural attractions in California seem to endure. More recently, the state's population growth has become driven more by natural internal increases and less by immigration.

Current official population forecasts for California extend to 2040, and indicate a state population of approximately 60 million. Plausible long-term projections of California's population in 2100 put California's population at 92 million (Landis and Reilly, 2002). For the larger Commission project, this is the "high" population growth scenario. This estimated 2100 population is distributed over California's landscape using detailed models of land use conversion (Landis and Reilly, 2002). Attachment B describes how we used these population estimates and accompanying urban land uses and land use densities to estimate 2100 economic (price-sensitive) demands for water by urban areas throughout California's intertied water supply system. Table 8 summarizes these projections, and Table 9 gives details of the projections for different urban areas, and urban areas to be, around the state. We discuss the land use aspects of these changes in the next section.

Table 8. Total CALVIN 2020 and 2100 population

	2020 projection	2100 projection	% increase
Population CALVIN	44,881,273	85,560,323	91
Population California	47,507,399	92,081,030	94
CALVIN urban water demand (MAF/yr)	10.06	19.38	61

Table 9. Percent population increase from California Department of Water Resources (DWR) 2020 projection to 2100 projection

Urban area	DWR 2020 population	2100 population	% population increase
Redding area	231,495	421,786	82
Yuba and surrounding area	210,450	442,266	110
Sacramento area	2,181,605	4,201,943	93
Napa-Solano	711,324	1,334,834	88
Contra Costa	565,353	896,486	59
East Bay Municipal Utility District (EBMUD)	1,326,460	1,961,825	48
San Francisco Public Utilities Commission (SFPUC)	1,501,900	1,987,120	32
Santa Clara Valley (SCV)	2,971,513	5,690,081	91
Santa Barbara-San Luis Obispo (SB-SLO)	713,675	1,534,167	115
Ventura	1,022,850	1,956,007	91
Castaic	688,500	1,156,443	68
San Bernardino Valley (SBV) Water District	878,944	1,016,582	16
Central Municipal Water District (MWD)	15,645,756	25,321,581	62
Eastern/Western MWD	2,251,030	5,381,640	139
Antelope Valley	1,079,650	1,821,155	69
Mojave River	1,075,775	4,395,538	309
Coachella	628,820	2,477,594	294
San Diego	3,839,800	8,078,707	110
Stockton	421,575	904,601	115
Fresno	1,142,125	1,429,670	25
Bakersfield	612,100	987,108	61
El Centro and surrounding area	214,250	977,078	356
Blythe	58,800	889,500	1413
CVPM 2	190,110	461,137	143
CVPM 3	42,275	125,008	196
CVPM 4	17,565	121,927	594
CVPM 5	358,800	371,471[a]	4
CVPM 6	894,299	368,680[a]	-59
CVPM 8	92,445	514,633	457
CVPM 9	391,700	753,932	92
CVPM 10	150,580	350,271	133

Table 9. Percent population increase from California Department of Water Resources (DWR) 2020 projection to 2100 projection (cont.)

Urban area	DWR 2020 population	2100 population	% population increase
CVPM 11	653,980	1,277,364	95
CVPM 12	297,770	727,016	144
CVPM 13	422,150	1,263,670	199
CVPM 14	69,375	97,531	41
CVPM 15	216,200	349,507	62
CVPM 17	294,210	1,060,199	260
CVPM 18	534,140	1,369,290	156
CVPM 19	41,100	95,210	132
CVPM 20	156,675	823,226	425
CVPM 21	84,150	166,539	98
Subtotal	44,881,273	85,560,323	91
Total California	47,507,399	92,081,030	94

a. Changed with regard to CALVIN 2020 model (detailed analysis units [DAU] originally shared with Yuba and Napa-Solano are transferred fully from CVPM 5 and CVPM 6 demands to Yuba and Napa-Solano, respectively).

Tables 10 and 11 detail 2020 and 2100 projections of total urban economic water demands in the CALVIN model. These economic water demands are estimated as detailed in Attachment B, incorporating consideration of urban water use efficiency practices, changes in land use density for various areas of the state, current local water prices, and current local water use rates. In all cases, these demands are represented in CALVIN as true, price-varying economic demands for water, with appropriate return flow rates back into the supply system. The large growth in population expected between 2020 and 2100 required that many of the small urban demands scattered throughout the Central Valley, which had been represented as fixed urban water uses, be updated to more complete economic representations of urban water demands (with price-sensitive water use). Table 11 gives the details on these new urban economic demand areas. The table also includes Blythe, a new urban area that had not previously been represented in the CALVIN model at all, but which is forecast to have a population of almost 900,000 by the year 2100, with accompanying water demands of 240 thousand acre-ft (TAF)/yr.

Table 10. CALVIN 2020 and 2100 urban water demands — existing economically represented urban demand areas in CALVIN

#	CALVIN node name	DAUs included	2020 demand TAF/yr	2100 demand TAF/yr	Description of major cities, agencies, or associations
20	Yuba City et al.	159, 168	64	116	Oroville, Yuba City
30	Sacramento area	172, 173, 158, 161, 186	678	1,061	Sacramento Water Forum, Isleton, Rio Vista, PCWA, EID, West Sacramento, North Auburn
50	Napa-Solano	191, 40, 41	149	260	Cities of Napa and Solano Counties
60	Contra Costa WD	192, 70% of 46	135	146	Contra Costa WD
70	EBMUD	70% of 47, 30% of 46	297	352	EBMUD
80	SFPUC	43	238	264	SFPUC City and County and San Mateo County service areas not in node 90
90	SCV	44, 45, 62, 30% of 47	658	928	Santa Clara Valley, Alameda County and Alameda Zone 7 WD
110	SB-SLO	67, 68, 71, 74, 75	139	269	Central Coast Water Authority
130	Castaic Lake	83	177	263	Castaic Lake Water Agency
140	SBV	44% of 100	282	285	SBVWD
150	Central MWD	87, 89, 90, 92, 96, 114, 56% of 100	3,731	3,899	Mainly Los Angeles and Orange County portions of Metropolitan Water District of Southern California (MWD)
170	Eastern and Western MWD	98, 104, 110	740	1,245	Mainly Riverside County portion of MWD
190	Antelope Valley area	SL3, SL4	283	420	AVEKWA, Palmdale, Littlerock Creek
200	Mojave River	SL5, CR1	355	1,397	Mojave Water Agency and High Desert Water Agency
210	Coachella Valley	CR4 (348, 349)	601	2,079	Desert Water Agency, Coachella Valley Water Agency
230	San Diego MWD[a]	120 + CR5	988	1,660	All of San Diego County
240	Stockton	182	95	176	City of Stockton
250	Fresno	233	384	447	Cities of Fresno and Clovis
260	Bakersfield	254	260	382	City of Bakersfield
Total			10,254	15,535	

a. Area expanded from 2020 CALVIN representation to include CR5.

Table 11. CALVIN 2020 and 2100 urban water demands — new 2100 economically represented urban demand areas in CALVIN

#	CALVIN node name	DAUs included	2020 demand TAF/yr	2100 demand TAF/yr	Description of major cities, agencies, or associations
10	Redding	141, 143	80	146	Redding
120	Ventura	81	219	368	Oxnard (Camarillo, Ventura)
270	El Centro et al.	All CR6	52	205	El Centro, Calexico, Brawley
280	Blythe et al.[a]	CR2, CR3	-	240	Blythe, Needles
308	CVPM 8 Urban	180, 181,184	26	134	Galt
311	CVPM 11 Urban	205, 206, 207	232	379	Modesto, Manteca
312	CVPM 12 Urban	208, 209	110	292	Turlock, Ceres
313	CVPM 13 Urban	210-215	161	412	Merced, Madera
317	CVPM 17 Urban	236, 239, 240	85	256	Sanger, Selma, Reedley, Dinuba
318	CVPM 18 Urban	242, 243	147	347	Visalia, Tulare
320	CVPM 20 Urban	256, 257	54	270	Delano, Wasco
Total			1,165	3,049	

a. Entirely new urban demand in 2100 CALVIN model.

An interesting aspect of these projections is the rates of population growth compared to rates of water demand growth. From 2020 to 2100, population is estimated to increase by more than 90%. But during this time, urban water demand might increase by only 61%. This implies a 16% decrease in per capita water use from 240 gpcd in 2020 to 202 gpcd in 2100. Given the spread of urban populations in the drier, hotter parts of California and the substantial sprawl that is expected to develop, this decrease in per capita applied water use is remarkable.

2.2 Land Use

Population growth will be accompanied by major changes in land use. Such land use changes have large implications for water use.

Expansion of urban land

As detailed in Attachment C and in Landis and Reilly (2002), urban development from 2020 until 2100 may cover an additional 1,350,000 additional acres of land (see Figure 5). Approximately 750,000 acres of this urbanization is likely to come from land currently being used for agriculture. In parts of the Central Valley, most urban growth is expected to be at lower

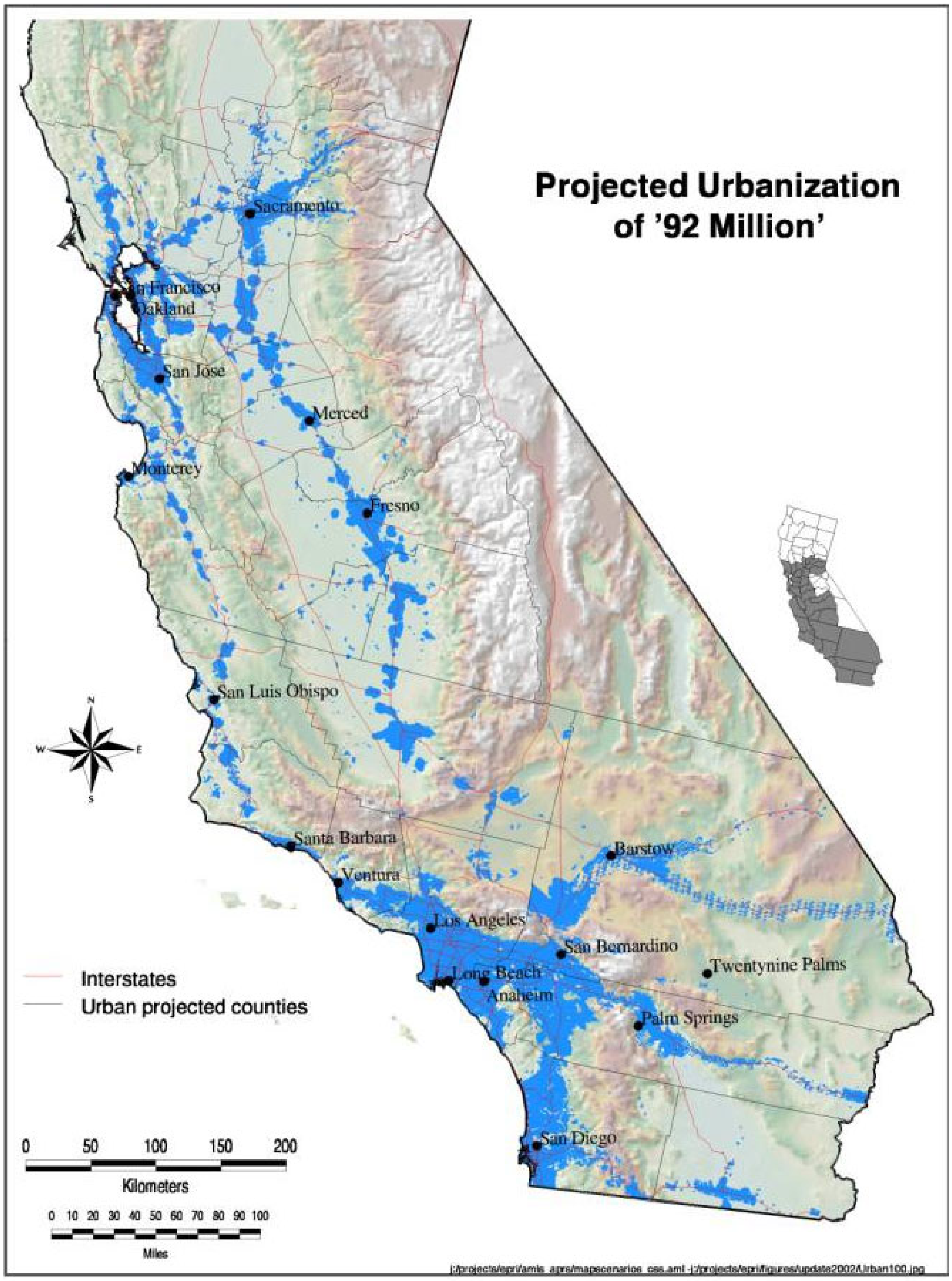

Figure 5. Urban land use 2100 (from Landis and Reilly, 2002).

than current average densities, because more of it will be in the form of lower density suburban development, leaving fewer opportunities for in-fill development. In other parts of California, greater densities of new urban growth are expected (Landis and Reilly, 2002).

Conversion of land from agricultural to urban uses

The conversion of 750,000 acres of land from agricultural to urban uses between 2020 and 2100 would reduce agricultural applied water use by roughly 2.7 MAF (Attachment C). This compares to estimated reductions in irrigated land of 325,000 acres from 1995 to 2020 from all causes (urbanization, agricultural drainage problems in the San Joaquin Valley, and increased competition in agricultural commodity markets; DWR, 1998). Although this conversion of what is now agricultural land is extensive, it will reduce total land in irrigated agriculture in California (now 9.5 million acres) by only about 11%. Agricultural use of land and water will remain the dominant human uses of land and water in California through 2100.

2.3 Wealth

The history of California has been one of mostly rising wealth, income, and living standards for the vast majority of the population. For this reason (as well as native optimism), this trend seems likely to continue.

Water use and wealth seem to be significantly correlated. Historically and currently, rising wealth correlates well with larger homes, larger yards, more use of water-intensive home appliances such as spas, and total water use. Studies in California often find that a 10% increase in household income raises water use by between 2% and 7% (Baumann et al., 1998).

Increasing wealth could easily justify estimates of greater per-household economic water demands in the future, but we have not done so in this study for several reasons.

First, we are particularly wary of estimates of the wealth of Californians in 2100. An assumed small annual rate of growth in real income leads to average wealth beyond our dreams in the year 2100. A 1% annual average increase in wealth leads to an average wealth 2.7 times current levels in 2100. A 2% annual increase in wealth grows to 7.4 times current household wealth in 2100.

Second, improvements in residential and commercial water use efficiency are expected to continue, perhaps fundamentally changing how wealth affects urban water use. In recent decades, growth in aggregate wealth has not led to growth in aggregate urban water use. Accordingly, we expect the effects of wealth increases on water use to decrease over time (Gleick et al., 1995).

We have some difficulty imagining the havoc on water demands that would be wrought from even modest projections of the increased wealth of Californians, assuming that recent historical correlations between wealth and urban water use continue. Multiplying exponential increases in income growth (even at low levels) by a significant correlation between income and water use over a very long period of time could lead to incredible quantities of average household water use.

Recoiling from this, and perhaps holding to "the sunnier side of doubt," we have neglected potential wealth effects on household and commercial water use for 2100. In this way, we expect to have underestimated urban water demands for 2100. This is one of many areas where long-term nonclimate changes will affect future water system performance and management.

2.4 Technology Improvements

Crop yields

In the last 100 years, technological improvements have increased crop yields, which have risen steadily at significant rates for many major crops. This has the long-term effect of increasing the water use efficiency of agriculture, in terms of crop yield per unit of water consumed, and of increases in the land area needed. For the postprocessed analysis, we extrapolated these trends until 2020, then extended the crop yield series at a low constant growth rate. Crop yields in the CALVIN agricultural penalty functions remain at 2020 levels.

Urban water demand

In the first half of the last century, urban per capita water use increased perhaps tenfold with increased wealth, water availability, new water-using appliances (such as low-flow toilets), and lower real prices. Urban water use (per capita) is now decreasing, with vastly lower rates of industrial water use and more efficient water use technologies. There is reason to believe that improvements in technology and a maturing economy have fundamentally changed the role and importance of water use for urban growth and prosperity. Urban and domestic activities are no longer as dependent on using large quantities of water as they have been in the past (Lund, 1988).

Water supply and treatment

Advances in water treatment technology may offer substantial improvements in the cost-effectiveness of additional water supplies from nontraditional sources. In particular, wastewater treatment for reuse has now become a significant minor supply for several areas of California, and is expected to increase in the future. Sea water desalination, with total capital and operating costs at a bit under $2,000/acre-ft today, may become cost-effective in the future.

To be effective for growing urban water demands, a new technology must offer (1) publicly acceptable assurances of water quality, (2) cost-effectiveness compared with the next best supply or demand alternatives, and (3) reliability. Currently, wastewater reuse has achieved this only to a limited degree, for only some urban uses, and often at a barely acceptable cost. For California, sea water desalination is merely experimental at this point. However, the technology does show some promise if its costs continue to decline and the costs of alternative options continue to increase.

2.5 Shifts in World Agricultural Commodity and Land Markets

Much of California's agricultural sector and water use responds to national and international agricultural commodity markets and prices. These world prices are likely to change in the future, but there is considerable uncertainty about how they might change. For postprocessing through the Statewide Water and Agricultural Production (SWAP) model, we assumed that the demand for California products would grow at past levels until 2020, and then expand as a function of U.S. population and income growth. (For the CALVIN model runs, agricultural economic penalty functions remain at 2020 levels.)

Changes in commodity prices and markets for agricultural products can directly affect the profitability of agricultural enterprises and thus the market price of agricultural land. If the world becomes more productive agriculturally and agricultural commodity process drop, farming as a commercial enterprise would become less profitable and agricultural land values would fall. Reductions in agricultural land prices make the use of such land for other uses more attractive. As for water, most urban land uses can already outbid agricultural uses for land, and so diminished agricultural land values would not likely increase urban sprawl greatly. However, lower agricultural land values would make acquiring agricultural land for environmental restoration or other public purposes more attractive. Agricultural land would also become more attractive for less commercial forms of agriculture, such as "hobby farms."

2.6 Changes in California Water Demands

Table 12 summarizes overall changes in California water demand volumes. Overall demands for water can be expected to increase, even accounting for decreases in agricultural water use that are driven in part by the urbanization of agricultural land.

Table 12. Summary of land and applied water demands for California's intertied water system (millions of acres and millions of acre-ft/yr)

Use	2020 land	2100 land	2020-2100 change	2020 water	2100 water	2020-2100 change
Urban				11.4	18.6	+7.2
Agricultural	9.2	8.4	0.75	27.8	25.1	-2.7
Environmental	-	-	-	-	-	-
Total	-	-	-	**39.9**	**44.5**	**+4.5 MAF/yr**

By comparing these changes in applied water demands with changes in water availability from Table 7, we can see that increases in water demands, even when mitigated somewhat by reductions in agricultural land and water use, might pose greater challenges for water management than climate warming. It is also plausible that climate warming could have a larger effect than net population growth changes. In any event, it is clear that there will be new challenges for water management in California's future.

3. Adaptations to Climate Change

People do not accept the weather or the climate passively. Humans have found ways to sustain themselves in some of the most extreme climates on earth, from the Arctic to the desert and from hurricane-pummeled coastlines to pestilential tropical forests and wetlands. Given the right political and economic conditions, civilizations have even thrived in a wide variety of climates. With substantially the same climate as today, rainfall-based commercial agriculture existed in the Negev Desert (Israel) during Roman and Byzantine times (Evenari et al., 1982). Human systems have an incredible array of means to respond and prosper to climatic and other changes (Stakhiv, 1998). How well could our modern civilization in California adapt to major changes in climate?

The state's complex water management system affords many opportunities to respond and adapt to challenges, whether they are from climate change or less exotic factors such as earthquakes, population growth, changes in water quality regulations, or other such stimuli. These water management responses, summarized in Table 13, are common for most types of water supply challenges.

Table 13. Summary of responses available

Response category	Response	Remarks or sources
Facilities	On-stream surface reservoirs	
	Off-stream surface reservoirs	
	Groundwater recharge	
	Well-field expansion	
	Water treatment	Includes desalting
	Water reuse treatment and redistribution	
	Water conveyance	Canals, pipelines, etc.
	Rainwater harvesting	Evenari et al., 1982
Operations	Seasonal changes	Seasonal flood control rules, hedging, and conjunctive use
	Over-year changes	Hedging and conjunctive use
	Improved forecasts	Yao and Georgakakos, 2001
Water allocation	Contract changes	
	Markets	Israel and Lund, 1995
	Exchanges	Lund and Israel, 1995
	Water rights	
	Pricing	
	Water scarcity	Reductions of water use functions for economic, social, and environmental purposes
Water use efficiency	Urban	
	Industrial	
	Agricultural	
	Environmental	Improved fish passage and habitat
Institutions	Governance and finance	Essential to implementing other responses

3.1 Facilities

Perhaps because we have historically used facilities to adapt our hydrologic environment to our desires for water use, we tend to think of modifying water management facilities to respond to climate change. Indeed, it is almost inevitable that facilities of some sort would change in response to significant climate change. Facility changes can include those that readily come to mind, such as reservoir or conveyance expansion; or those that are more novel, such as expansions of groundwater infiltration and pumping capacity to allow for greater conjunctive use of surface and groundwaters; or those ideas that would merely be new for California. These could include technologies that make useless or problematic waters useful (at some cost), such as rainwater harvesting from hill slopes or water treatment technologies (including perhaps desalting).

Each type of facility in Table 13 interacts with others based on their geometric configuration capacities and their operations. It is not always obvious which type of facility, or combination of facilities, would be the most effective for a given region or for a particular form of climate change. Addressing such questions typically requires insights that we can gain from detailed computer modeling studies.

3.2 Operations

Operating a set of facilities in a hydrologic environment to accomplish a set of water management objectives is a complex business, especially in an extensive and heterogeneous system such as California's. The operation of a given set of infrastructure components has several effects on water deliveries, quality, costs, and environmental performance.

Delivery quantities and reliability

Conveyance operations have important implications for water supply reliability. By better coordinating the use of water conveyed from different sources, more effective and complete use can be made of a region's or a state's water resources, losses or costs can be reduced, and reliability can be increased. These operations also have water quality and cost implications.

Hedging allows system operators to reduce the probability of severe water shortages by withholding water in reservoirs when it is otherwise available. This practice keeps more water in reservoirs, but it also induces small amounts of scarcity in more average and dry years when there is enough water to supply all normal demands. This creates a trade-off between less water more reliably, or more water on average with greater variability.

Storage allocation allows system operators to place water in locations that reduce water losses resulting from evaporation or seepage, and to minimize the amount of "spilled" water during wet periods. This increases total water availability, although it might increase conveyance costs or change water quality. Such "conjunctive" use of surface and groundwater is an important aspect of allocating and using stored water.

Water quality

Especially in California, the mixing of water sources has important water quality effects on all types of water users. These effects affect environmental performance, agricultural productivity and sustainability, and urban costs and consumer satisfaction. Storage, conveyance, and treatment facilities of all sorts often have important roles to play in terms of water quality.

Water cost

The operating costs of a system include pumping, water treatment, wastewater treatment, and maintenance costs, all of which can vary with operations, as well as fixed administrative and maintenance costs. In addition, there are negative costs on water systems, such as hydropower generation and recreation benefits and revenues.

Environmental performance

The operation of reservoirs, pumps, and diversions can have well-known effects on environmental species and ecosystems. These effects can be interactive and cumulative.

3.3 Water Allocations and Scarcity

Allocating water among users is always controversial but unavoidable when water is scarce or threatens to become scarce. A variety of water allocation approaches are available. Current water rights, contracts, and regulations constitute a system of water allocation. We supplement this system with contract changes, water markets, and water exchanges, as well as by using water prices (in a market or banking setting) to encourage the movement of water to higher valued uses with economic compensation to holders of water rights.

Water allocation options often imply scarcities for some water users. When supplies are limited, water scarcity is the deliberate curtailment of water deliveries to some users, so as to maximize benefits across the system. Akin to water rationing or cutbacks to agricultural water allocations during drought, this is a conscious decision to limit water use for some or all water users. All water use sectors can suffer from such scarcities.

3.4 Water Use Efficiency

Water use efficiency options are intended to attain similar levels of economic, social, or environmental performance with less water, and efficiency options exist for all sectors that use water. For urban uses, examples of use efficiency options are toilet retrofits that reduce water use per flush and xeriscape landscaping that attains similar garden desirability with less water.

Agricultural water use efficiency options would include improvements in irrigation or drainage technology or enhancements to cultivars designed to reduce water consumption per unit of crop output. Because of reuse of crop return flows to surface and groundwaters, consumed water per unit of crop yield is a better indicator of efficiency than water applied per unit of crop output. Environmental water use efficiency might include introducing fish ladders that require less bypass flow, or improving channel morphology to result in similar habitat with less streamflow.

3.5 Institutions

Physical, operational, and technical water management activities are implemented and financed within an environment of institutions. These institutions begin with millions of households and thousands of businesses (farms, other industries, and commercial users) that make water use decisions with various personal, social, and economic objectives in mind. Many hundreds of local water suppliers, city water departments, irrigation districts, and suburban water purveyors influence these decisions through their conditions of water use such as prices, rationing policies, regulations, and incentives. Many local water suppliers take water from larger water projects or agencies, or must otherwise interact at regional levels to receive water supplies. These larger projects and water sources have a host of financial, regulatory, and other institutional aspects that affect how they operate and respond. Finally, at the state level (and to a lesser degree the national level), water management decisions are affected by state water rights, regulatory policies, plumbing codes, financing arrangements, and available technical information.

Unlike the society and pyramids of ancient Egypt, the pyramid of California water management is led primarily from its broad base. Most leadership of, authority over, and funding sources for water management in California are based at local levels, with implementation authority and funding capabilities diminishing toward the “summit” of state authority. The days of state and federal water projects developing large statewide systems seem to be over, for practical technical, economic, and political reasons. Historically, in the United States and most of the developed world, water supply is a local responsibility, predominantly funded locally, with occasional regional cooperation and coordination.

However, state and federal activities are not unimportant. These governments are likely to continue to be involved in their respective large-scale water projects, providing wholesale water to much of California, either as project owners and operators or as project regulators. State and federal governments also furnish a legal context for local actions and activities, in terms of contract law, environmental regulations, and administrative law. State government is especially important here because it governs the system of water rights, ownership, and environmental regulation. Early California water development was hampered significantly for about 50 years by legal disputes over water right systems (Hundley, 2000). Local and regional entities cannot make good decisions in a context of uncertainties about water rights. Such future political and legal outcomes are not subject to the results of computer models.

3.6 Interaction of Responses

The responses we outlined above are all part of a very complex water system. It is highly unlikely that the most effective response to any catastrophe or change in the system would be in the form of a single response. A concerted combination of responses is likely to be required and desirable. For a complex system, identifying and exploring combinations of responses to a major change in its operating environment typically requires that computer modeling be used. In the next section, we discuss the application of the CALVIN economic-engineering optimization model to estimate impacts and identify promising adaptive responses to climate change in California's water supply system.

4. Modeling Adaptation with CALVIN

The method applied here uses the system optimization model CALVIN to estimate system-wide changes in both performance and desirable management (Jenkins et al., 2001; Draper et al., in press). This approach is unique for studies of climate change in California. Some limitations of this approach are detailed by Jenkins et al. (2001) and explored by Draper et al. (in press). The approach taken in this study advances the climate warming simulation studies of Lettenmaier and Sheer (1991), VanRheenen et al. (2001), and others in several ways: (1) the spatial analysis is more extensive and integrated, covering more of California and including groundwater; (2) the spatial hydrology is more extensive and detailed; (3) the optimization model employed is far more adaptable than the simulation model; (4) economic performance results are generated and reported explicitly; and (5) future water demands are incorporated into the results (because climate change will occur under different water demand circumstances than we are experiencing today).

4.1 What is CALVIN?

The CALVIN model explicitly integrates the operation of water facilities, resources, and demands for California's vast intertied water system. It is the first model of California water where surface waters, groundwater, and water demands are managed simultaneously across the state. The CALVIN model covers 92% of California's population and 88% of its irrigated acreage (Figure 6), with roughly 1,200 spatial elements, including 51 surface reservoirs, 28 groundwater basins, 18 current urban economic demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and

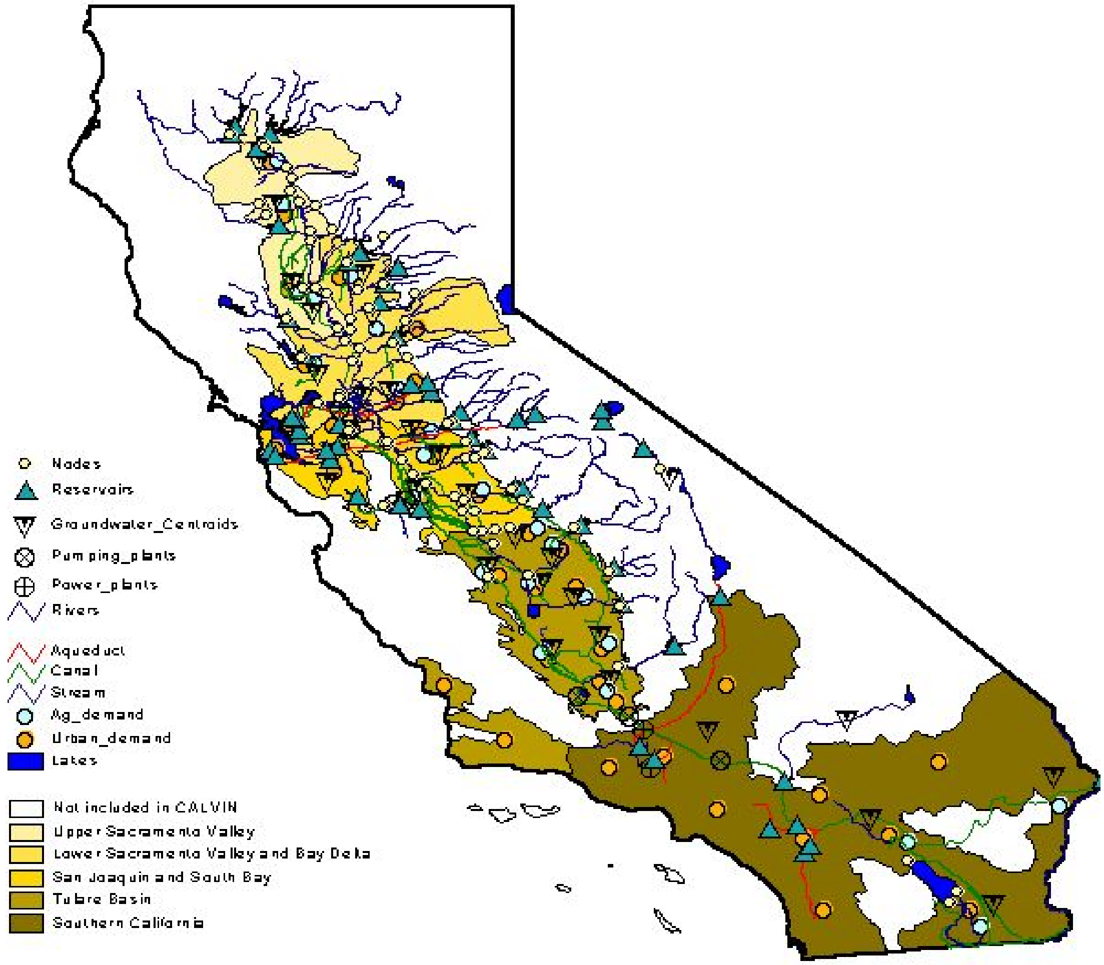

Figure 6. Demand areas and major inflows and facilities represented in CALVIN.

numerous conveyance and other links representing the vast majority of California's water management infrastructure. This detailed and extensive model has necessitated the assembly and digestion of a wide variety of data within a consistent framework. The model's detailed schematic and documentation can be found at cee.engr.ucdavis.edu/faculty/lund/CALVIN/.

The second major aspect of the CALVIN model is that it is an economically driven engineering "optimization" model. The model, unless otherwise constrained, operates facilities and allocates water to maximize statewide agricultural and urban economic value from water use. This pursuit of economic objectives is initially limited only by water availability, facility capacities, and environmental and flood control restrictions. The model can be further constrained to meet operating or allocation policies, as is done for the base case.

Figure 7 illustrates the assembly of a wide variety of relevant data on California's water supply, the systematic organization of the data, and the documentation of the data in large databases for input to a computer code (HEC-PRM). The model then finds the "best" water operations and allocations for maximizing regional or statewide economic benefits, and indicates the variety of outputs and their uses that can be gained from the model's results.

More than a million flow, storage, and allocation decisions are suggested by the model over a 72-year statewide run, making it among the most extensive and sophisticated water optimization models constructed to date. The model produces a wide range of water management and economic outputs.

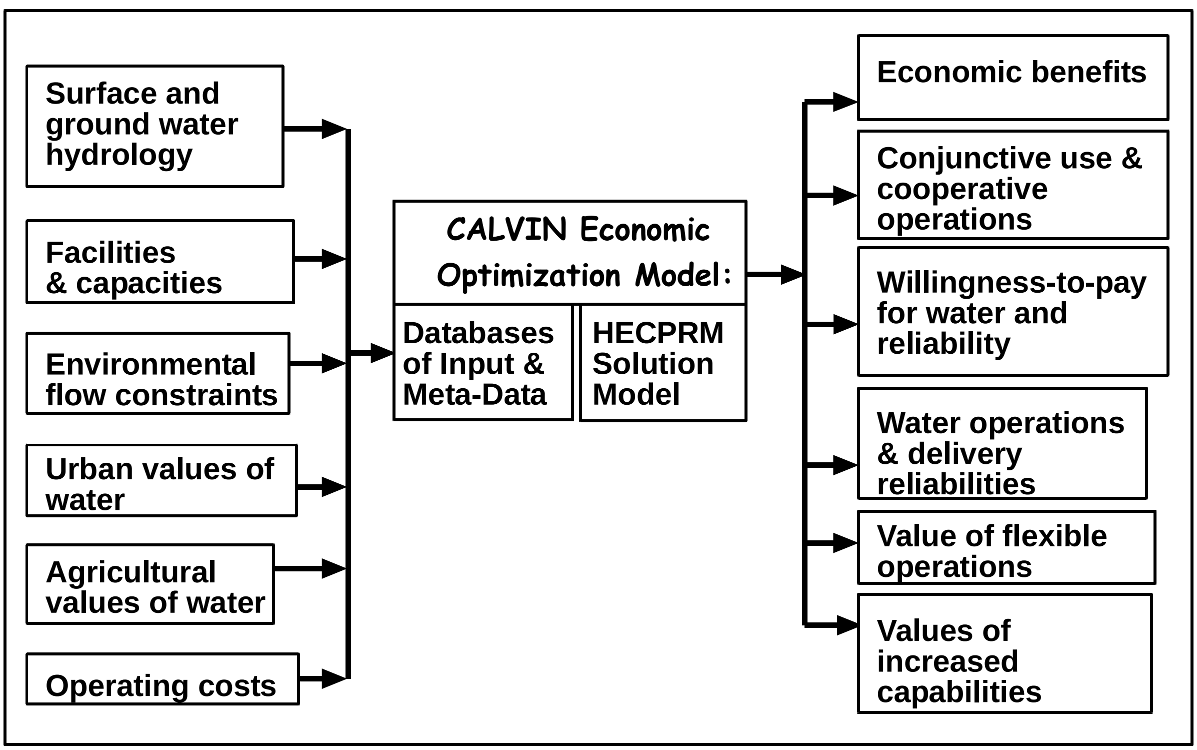

Figure 7. Data flow schematic for CALVIN.

Uses

Results from the CALVIN model can be used for a wide variety of policy, planning, and operations planning purposes, including:

- identifying economically promising changes in reservoir, conveyance, recharge, and recycling facility capacities at the local, regional, and state levels

- determining promising operational opportunities, such as:

    - conjunctive use of surface water and groundwater
    - cooperative operations of supplies
    - water exchanges and transfers
    - water conservation and recycling
    - improved reservoir operations

- assessing user economic benefits or willingness to pay for additional water

- presenting physically possible and economically desirable water management policies independently and in a relatively rigorous way

- identifying promising solutions for refinement and testing by simulation studies

- providing preliminary economic evaluations of proposed changes in facilities, operations, and allocations.

In addition, the model demonstrates several improvements in analytical methods that should be of long-term value to the state. These technical improvements include:

- feasibility of economic-engineering optimization of California's water supplies

- data assessment, documentation, and partial reconciliation for surface water, groundwater, and water demand data from the entire state

- advances in modeling techniques, documentation, and transparency.

These improvements in data management, methods, and concepts offer the potential for significant and sustained long-term improvements in California water management.

Innovations

The CALVIN model and its approach differ from current large-scale simulation models of California and from other optimization models of parts of the state. CALVIN's major innovations include:

- Statewide modeling with all major parts of California's intertied system from Shasta-Trinity to Mexico allows water supply issues to be examined more comprehensively.
- Groundwater is explicitly included and operated in all regions represented in the model, which aids in examining conjunctive use alternatives.
- Economic performance is the explicit objective of the model, facilitating economic evaluation of capacity alternatives, conjunctive operations, and water transfers, as well as estimation of user willingness to pay for additional supplies.
- Surface and groundwater supplies and water demands are operated in an integrated manner, allowing for the most economic system adaptation to new facilities or changes in demands or regulations.
- Economic values of agricultural and urban water use are estimated consistently for the entire intertied system.
- Data and model management have been fundamental to model development — all major model components are in the public domain and the model assumptions have been extensively documented.
- A systematic analytical overview of statewide water quantity and economic data was undertaken to support the model.
- The model suggests new management options for water exchanges and markets, cooperative operations, conjunctive use of ground and surface waters, and capacity expansion.
- Using optimization allows promising alternatives to be rapidly and impartially screened before more detailed consideration and analysis is undertaken.

Such innovations are crucial to support the search for technically workable, politically feasible, and socially desirable solutions to water problems in California.

Table 14. Previous optimization studies using HEC-PRM

Year(s)	Basin (number of reservoirs)	Study purpose(s)	Citation(s)
1990-1994	Missouri River (6)	Economic-based reservoir system operating rules	U.S. Army Corps of Engineers (USACE), 1991a, 1991c, 1992a, 1992b, 1994b; Lund and Ferreira, 1996
1991-1996	Columbia River System (14)	Economic-based reservoir operating rules, capacity, expansion, multipurpose operations, seasonal operations	USACE, 1991b, 1993, 1995, 1996
1997	Carson-Truckee System (5)	Prioritization of uses and performance assessment	Israel, 1996; Israel and Lund, 1999
1997	Alamo Reservoir (1)	Multiobjective reservoir operation	Kirby, 1994; USACE, 1998b,c
1998	South Florida system (5)	Capacity expansion and multiobjective performance	USACE, 1998a; Watkins et al., 2003
1999	Panama Canal System (5)	Drought performance and economic reservoir operations	USACE, 1999
1999-present	Models of 5 California regions	Calibration of statewide model and study of regional market potentials	Appendices 2A, 2B, 2C, 2D, and 2E of Jenkins et al., 2001; Newlin et al., 2002
1999-present	California intertied system (79)	Economic capacity expansion, water markets, and financing	Howitt et al., 1999; Jenkins et al., 2001; Draper et al., in press

Note: For references, see Jenkins et al., 2001.

In the past decade, the HEC-PRM network flow solution software and the general approach of the CALVIN model have been applied to numerous other geographic locations, as listed in Table 14. Although the application of CALVIN in California represents the largest such undertaking, other applications have included some of the largest water resource systems elsewhere in the nation.

The method employed for this study contributes several advances over previous efforts to understand the long-term effects of climate warming on California's water system, and on long-term water management in general. These include:

- **Comprehensive hydrologic effects of climate warming**. This includes all major hydrologic inputs (major streams, groundwater, local streams, and reservoir evaporation). Groundwater, in particular, represents 30%-60% of California's water deliveries and 17% of natural inflows to the system.

- **Integrated consideration of groundwater storage**. Groundwater contributes about 75% of the storage used in California during major droughts.

- **Statewide impact assessment**. Previous explorations of climate change's implications for California have examined only a few isolated basins or one or two major water projects. However, the state has a very integrated and extensive water management system. This system continues to be increasingly integrated in its planning and operations over time. Examining the ability of this integrated system to respond to climate change is likely to require that the entire system be evaluated.

- **Economic-engineering perspective**. Water in itself is not important — it is the ability of water sources and a water management system to supply water for environmental, economic, and social purposes that is the relevant measure of the effect of climate change and adaptations to climate change. Traditional "yield"-based estimates of climate change effects do not offer results as meaningful as economic and delivery-reliability indicators of performance.

- **Incorporation of multiple responses**. Adaptation to climate change will not be through a single option, but through many traditional and new water supply and management options working in concert. The CALVIN model can explicitly represent and integrate a wide variety of response options.

- **Incorporation of future growth and change in water demands**. Climate change will have its greatest effects some decades from now. During this time, population growth and other changes in water demands are likely to exert major influences on how water is managed in California and how well the system performs.

- **Optimization of operations and management**. Most previous climate change impact studies on water management have been simulation-based. Because major climate changes are most likely to occur only after several decades, it seems unreasonable to employ current system operating rules in such studies. Fifty years from now, today's rules will be archaic. An optimization approach seems to be more reasonable, as water management systems must always adapt to future conditions. The limitations of optimization seem less burdensome than the limitations of simulation for exploratory analysis of climate change policy and management problems.

Limitations

All computer models have limitations. The limitations of the CALVIN model arise from three main sources, as detailed in Chapter 5 of Jenkins et al. (2001) and Draper et al. (in press):

1. The input data used to characterize surface and groundwater supplies, water demands, and base case operations in the CALVIN model are limited by the quality of existing data sets and by weak or unavailable information for some parts of the state, as well as by our own project time constraints. The CALVIN calibration, with its own limitations, attempts to rectify and resolve inconsistencies in data sets to achieve an integrated surface and groundwater hydrologic balance for the Central Valley. Similarly, for climate studies, characterization of climate inputs is a source of potential limitations.

2. Choice of a network flow with gains optimization solver (HEC-PRM) imposes several restrictions on the model's ability to represent the system accurately. In particular, flow relationship constraints such as those involved in environmental regulation, water quality, and stream-aquifer and other groundwater behavior must be simplified. In addition, water allocation and storage decisions are biased somewhat by perfect foresight in the deterministic optimization solution. This last issue has been examined in some detail (Draper, 2001; Newlin et al., 2002), but merits consideration when interpreting results and further work.

3. Exclusion of flood control and recreation benefits from reservoir operations in this initial model development may distort operations of some parts of the model and limit the identification of opportunities for storage reoperation. It does, however, make interpreting CALVIN results somewhat easier. This limitation reflects mainly a time constraint on model development. This project added hydropower representation to the earlier version of CALVIN.

4.2 Model Modifications for Climate Change Study

A major modification to the CALVIN model for this study was the addition of hydropower on many of the system's surface reservoirs. Hydropower impacts of climate change are likely to be extensive, and hydropower benefits are an important aspect of operating California's water system. Attachment D contains the details of hydropower representation in CALVIN.

More minor permanent modifications to the model include updates to the environmental flow and operations constraints (Attachment E) and the correction of some small errors in the earlier model version.

For this particular climate change study, for the 2100 time horizon with 2100 demands, we made several additional modifications:

- Changes in hydrology and water availability were made for surface and groundwater sources throughout the system to represent different climate warming scenarios.
- Estimates of 2100 urban and agricultural economic water demands were used.
- Coastal areas were given unlimited access to sea water desalination at a constant unit cost of $1,400/acre-ft.
- Urban wastewater reuse was made available above 2020 levels at $1,000/acre-ft, up to 50% of urban return flows.
- Local well, pumping, and surface water diversion and connection and treatment facilities were expanded to allow access to purely local water bodies at appropriate costs.

4.3 Model Runs

We used several statewide model runs to evaluate the potential impact of climate change on California with and without population growth and adaptation. These runs can be summarized as:

- **Base 2020**: This run represents projected water supply operations and allocations in 2020, assuming that current operation and allocation policies continue. This run was prepared for CALFED and is extensively documented elsewhere (Jenkins et al., 2001; Draper et al., in press).
- **SWM (Statewide Water Market) 2020**: This run represents operations, allocations, and performance in 2020, assuming flexible and economically driven operation and allocation policies. This optimized operation can be understood as representing the operation of a statewide water market or equivalent economically driven operations. This run was also prepared for CALFED and is extensively documented elsewhere (Jenkins et al., 2001; Draper et al., in press).
- **SWM 2100**: This run extends the SWM 2020 model and concept for 2100 water demands, but retains the same (historical) climate used in Base 2020 and SWM 2020.
- **PCM 2100**: Using the same 2100 water demands as SWM 2100, this run employs the PCM 2100 climate warming hydrology described in Section 2.

- **HadCM2 2100**: Using the same 2100 water demands as SWM 2100, this run employs the HadCM2 2100 climate warming hydrology described in Section 2.

For the SWM 2100 and PCM 2100 runs, two optimization runs were performed, with and without a more sophisticated representation of hydropower operations (explicitly modeling variable hydropower heads versus the simpler and more approximate implicit representation of hydropower head). For the purposes of this appendix, we found no significant differences in the results from these two representations of hydropower. This subtlety is discussed in more detail in Attachment D.

4.4 Economic Impacts and Adaptation for Climate Changes

Figure 8 summarizes the average water availability to each region of California under the historical hydrology and the two climate warming scenarios. Compared with the historical hydrology, PCM 2100 is much drier and HadCM2 2100 is much wetter. Note also that the Southern California region is not greatly affected hydrologically by these changes.

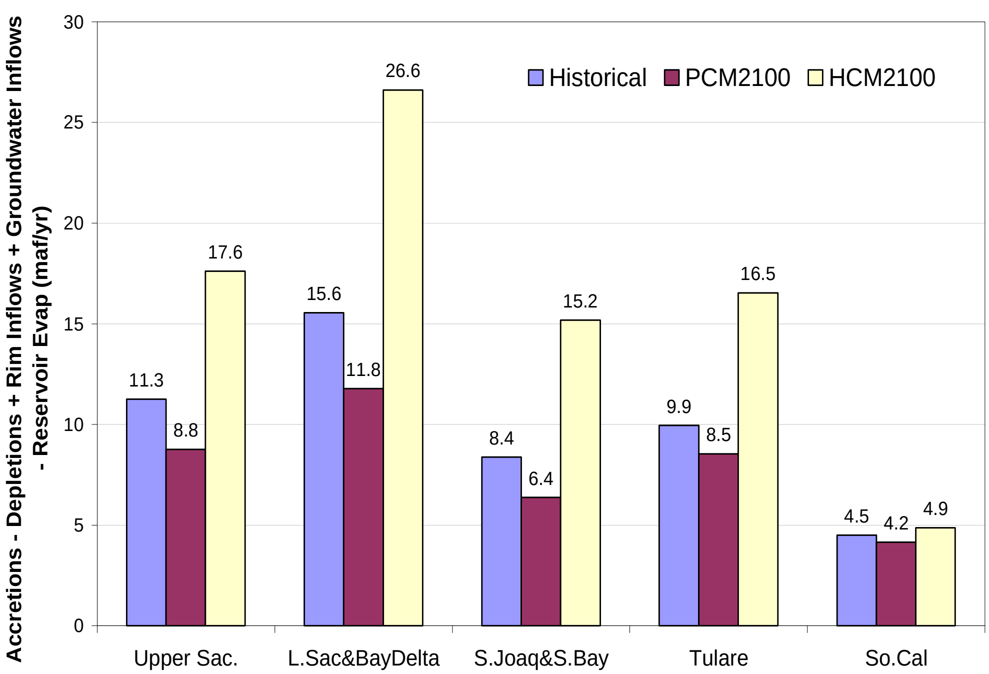

Figure 8. Water availability in each region for three climate scenarios.

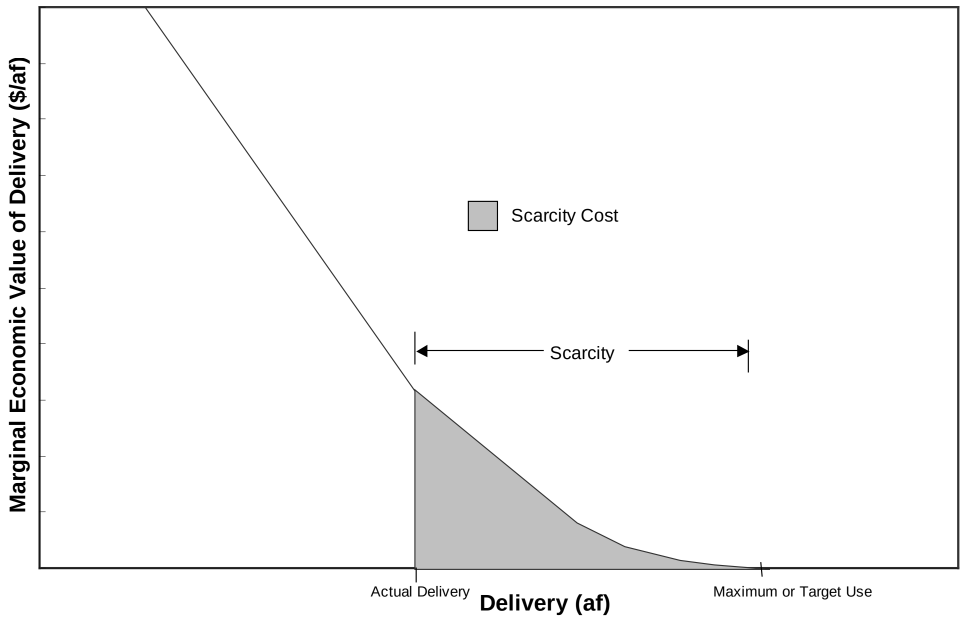

Figure 9. Definition of scarcity and scarcity cost for a water user.

Economic costs of water scarcity and operations

As Figure 9 shows, water scarcity is the difference between the amount of water delivered and that water user's desired delivery if water were free and unfettered in its availability. Scarcity cost is a water user's economic loss from this scarcity of water supply or their willingness to pay for deliveries to the maximum level.

Table 15 summarizes the economic performance of California's water system under the five scenarios modeled. In all cases, operating costs greatly exceed scarcity costs seen by water users, although operating costs vary less among climate change scenarios than scarcity costs. Population growth alone leads to a $4.1 billion/yr increase in water operations and scarcity costs to California, including almost a fivefold increase in water scarcity costs over a similarly optimized SWM 2020. Adding a dry climate warming hydrology (PCM 2100) further increases total costs by $1.8 billion/yr, most of which are scarcity costs in the agricultural sector. The wet climate warming scenario (HadCM2 2100) reduces scarcity and operating costs to all sectors by $250 million/yr overall, most of which are reduced operating costs.

Table 15. Summary of statewide operating[a] and scarcity costs

Cost	Base 2020	SWM 2020	SWM 2100[b]	PCM 2100[b]	HadCM2 2100[b]
Urban scarcity costs	1,564	170	785	872	782
Agricultural scarcity costs	32	29	198	1,774	180
Operating costs	2,581	2,580	5,918	6,065	5,681
Total costs	**4,176**	**2,780**	**6,902**	**8,711**	**6,643**

a. Operating costs include pumping, treatment, urban water quality, recharge, reuse, desalination, and other variable operating costs. Scarcity costs represent how much users would be willing to pay for additional water deliveries.

b. Agricultural scarcity costs are somewhat overestimated because about 2 MAF/yr of reductions in Central Valley agricultural water demands (which result from the urbanization of agricultural land) are not included.

Total water deliveries and scarcities for the five scenarios are shown in Figure 10, across the state and for each of five major regions. Water demands statewide and for each region increase as a result of urbanization. Southern California surpasses Tulare Basin as the major water-consuming region of California. With the exception of Southern California, all regions have small but manageable water scarcities in 2100 with historical and HadCM2 2100 hydrologies. With PCM 2100's dry hydrology, significant scarcities exist in all regions, although Southern California's scarcity amounts are not greatly changed.

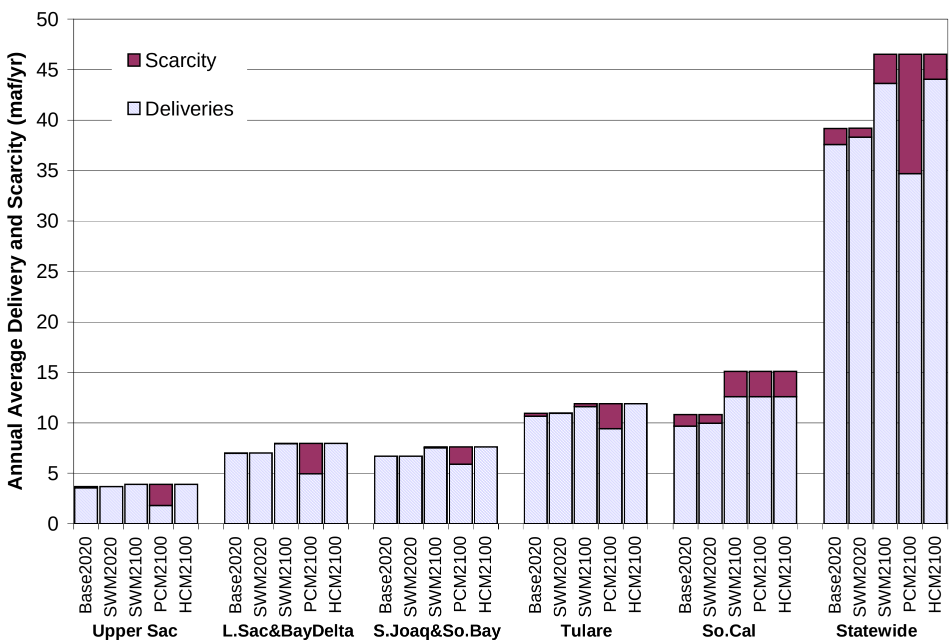

Figure 10. Total water deliveries and scarcities by region and statewide.

Figure 11 shows water deliveries and scarcities by region and across the state for agricultural users only. These figures are overestimated by perhaps 2 MAF/yr because Central Valley agricultural water demands were not reduced to correct for the urbanization of agricultural land. This correction should be approximately 2 MAF/yr across the Central Valley. Nevertheless, in 2100, agriculture remains the largest user of water in California. In Southern California, agricultural water use drops substantially because of the urbanization of agricultural land and the sale of agricultural water to urban users via the Colorado River Aqueduct, the Coachella canal, and other canals serving major urban areas within the Colorado River watershed. Under the dry PCM 2100 hydrology, major agricultural scarcities are seen in Central Valley agriculture, amounting to about 50% of agricultural water demands in some regions. Except for Southern California, these problems disappear with the wetter HadCM2 2100 hydrology.

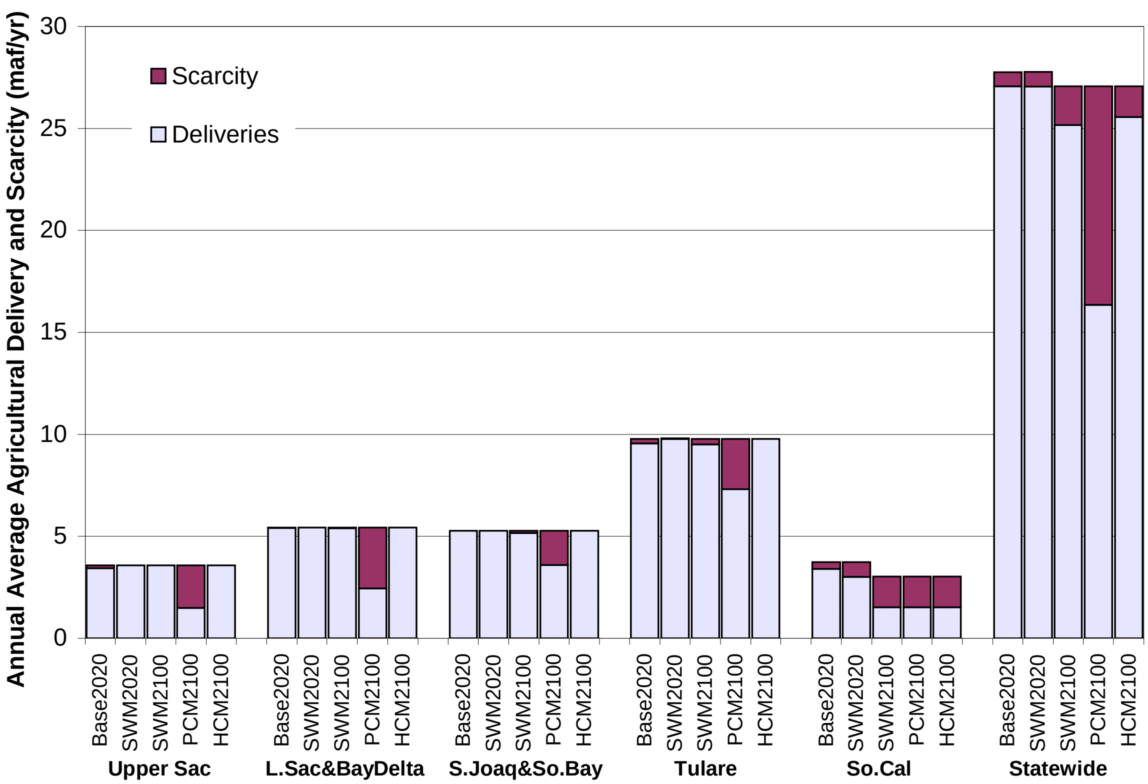

Figure 11. Agricultural water deliveries and scarcity by region and statewide.

As we can see in Figure 12, urban water deliveries are much less affected by growth and climate warming. This insensitivity has several causes. First, urban water use has higher marginal economic values. In the optimization model, this allows urban areas to purchase water from other users and to bear expenses for wastewater reuse and desalination that would be unacceptable for agricultural users. Second, despite significant growth, urban users continue to represent a lesser proportion of water demands in most of California, so that for non-Southern California regions, water can be purchased from agricultural water users. Third, Southern California, where urban water use becomes the major use category, is hydraulically isolated by the already limited conveyance capacity on the California and Colorado aqueducts and is also relatively less affected by climate warming hydrologic changes.

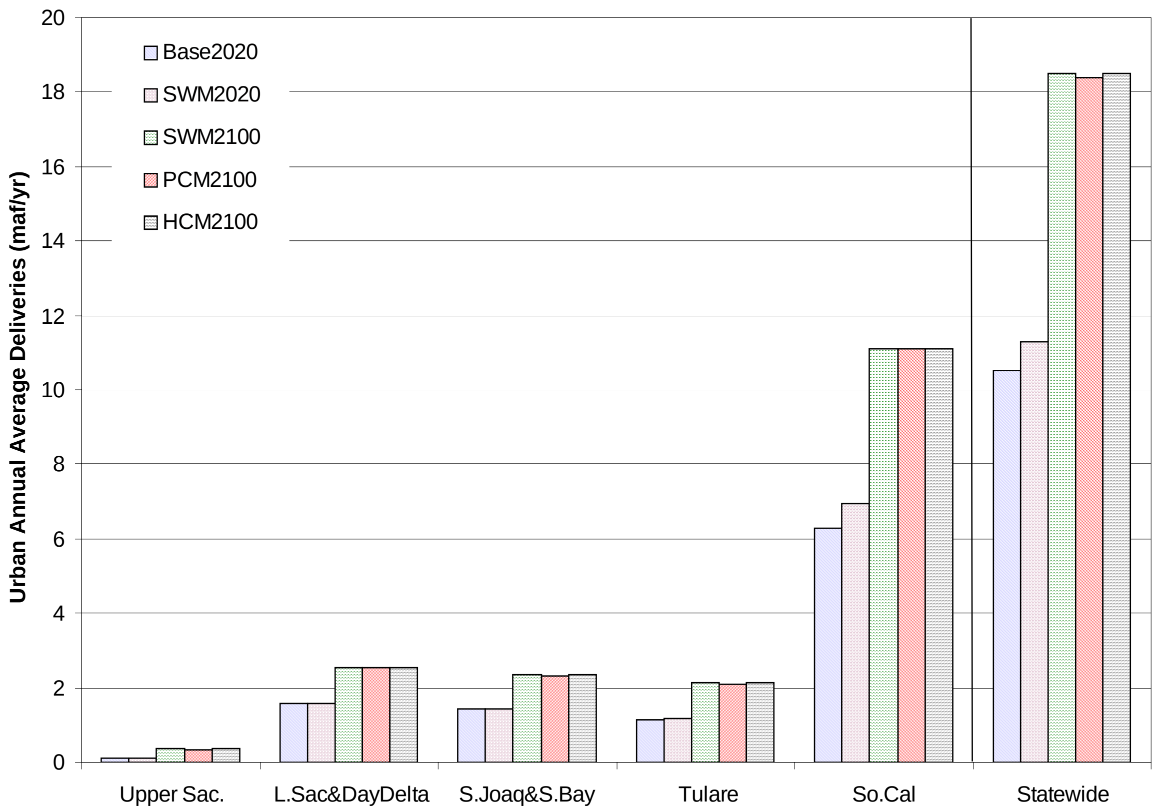

Figure 12. Total urban water deliveries by region and statewide.

The overall effect, seen in Figures 13 and 14, is that 2100 urban water scarcity and scarcity costs are relatively insensitive to climate change. Urban areas implement roughly 1 million acre-ft/yr of additional water conservation, which this model sees as scarcity (with an associated urban scarcity/conservation cost). This urban conservation/scarcity changes relatively little among the different climate scenarios. Economically, agricultural water users are much more sensitive to climate changes, because the model assumes that urban areas can purchase much of the water they need from agricultural areas under unfavorable climates. Arguably, much of Central Valley agriculture would likely disappear or change to less productive dryland farming given very dry forms of climate warming, such as PCM 2100, leaving the larger urban water economy relatively unaffected.

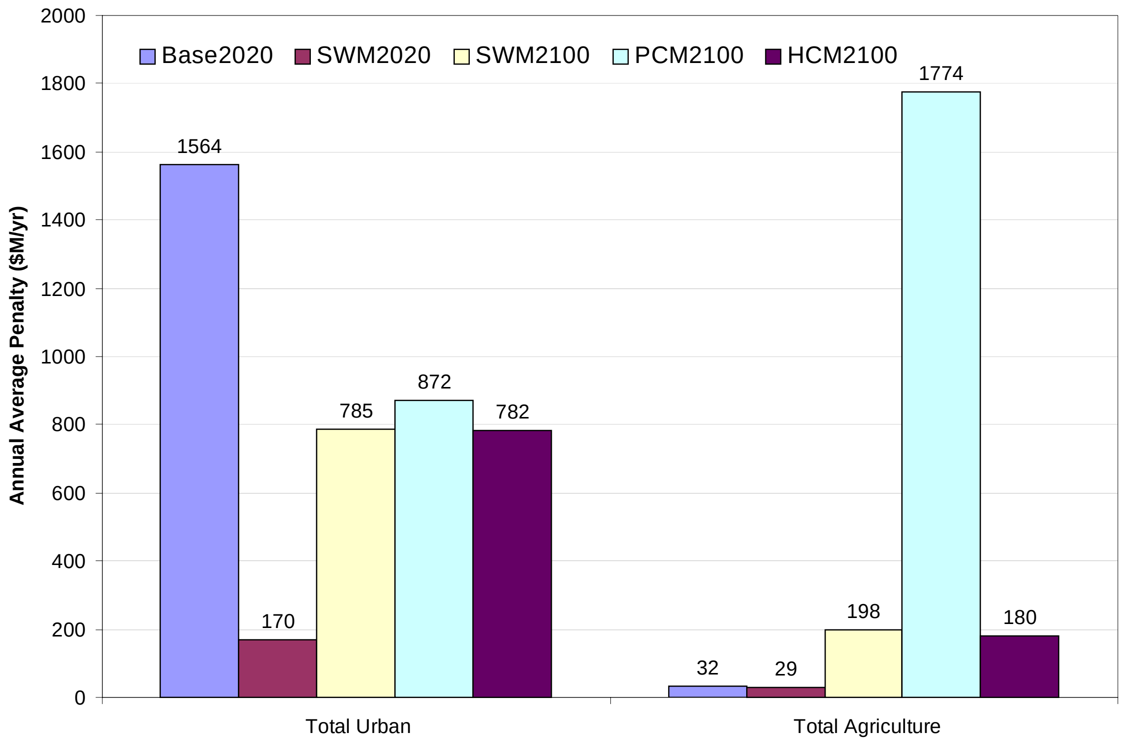

Figure 13. Average annual economic scarcity cost by sector.

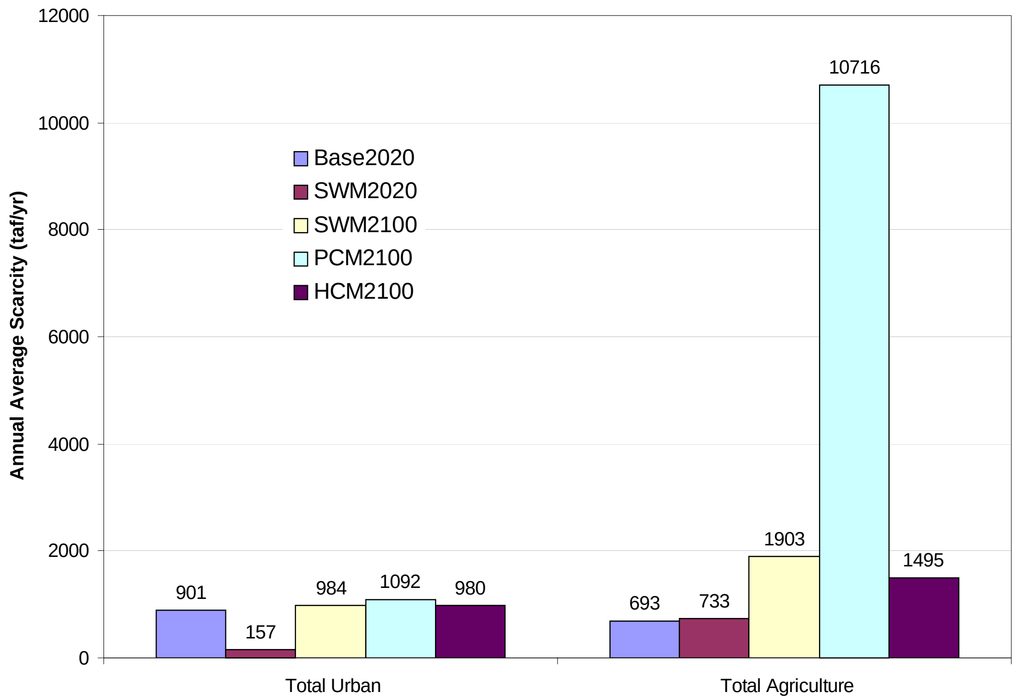

Figure 14. Total volumetric scarcity.

The varying regional and sectoral characters of these scarcities, along with scarcity costs and sensitivities to population growth and climate warming, are shown in greater detail in Figures 15 and 16 and Tables 16 and 17. The sensitivities of a region and sector are driven by competitive forces such as the relative values of water uses in the context of relative water availabilities and the availability of conveyance capacity to move water between regions.

For the urban areas, water scarcities generally imply water conservation measures. The demand curves used to estimate water scarcity costs represent consumers' willingness to use less water in exchange for lower water costs. Much of urban customer response to water scarcity therefore takes the form of installing water-conserving plumbing fixtures, landscaping that requires less water, and various other water conservation actions, which often create inconvenience costs to consumers.

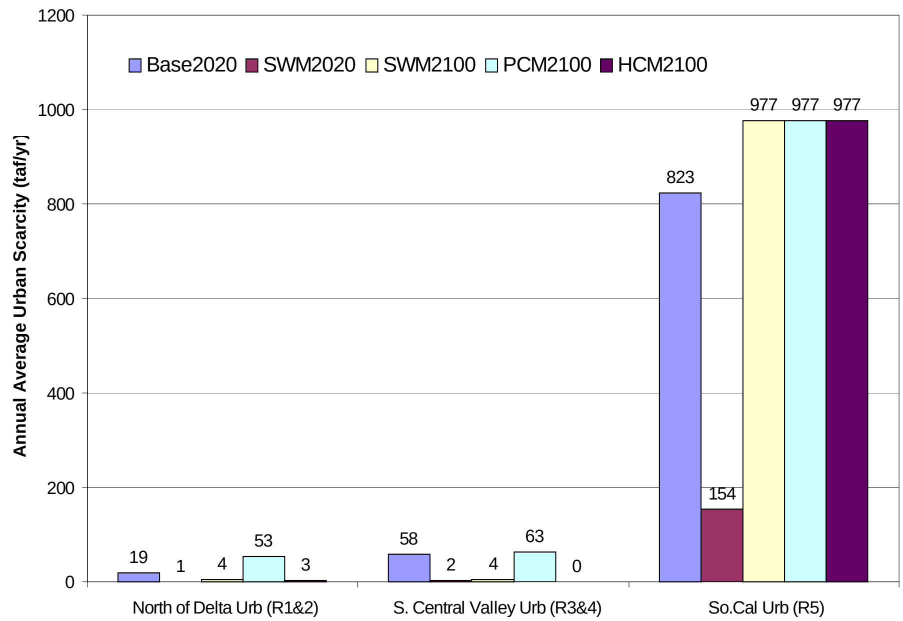

Figure 15. Urban scarcity cost by region.

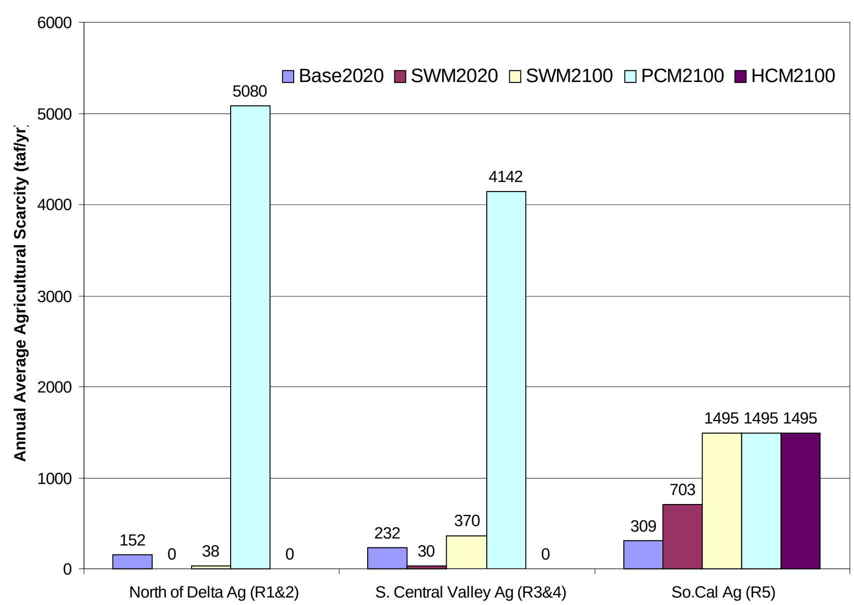

Figure 16. Agricultural scarcity cost by region.

Table 16. Water scarcity costs for agricultural economic demand areas ($ million/yr)

Demand area	**Base 2020**	**SWM 2020**	**SWM 2100**	**PCM 2100**	**HadCM2 2100**
CVPM 1	0.0	0.0	0.0	11.5	0.0
CVPM 2	3.5	0.0	0.2	72.8	0.0
CVPM 3	3.1	0.0	0.0	215.5	0.0
CVPM 4	0.0	0.0	0.0	48.4	0.0
CVPM 5	0.0	0.0	0.2	240.4	0.0
CVPM 6	0.0	0.0	0.3	30.9	0.0
CVPM 7	0.0	0.0	0.0	74.9	0.0
CVPM 8	0.0	0.0	0.0	86.9	0.0
CVPM 9	0.2	0.0	0.0	42.9	0.0
CVPM 10	0.0	0.0	1.6	52.9	0.0
CVPM 11	0.0	0.0	0.0	68.6	0.0
CVPM 12	0.0	0.0	0.0	53.0	0.0
CVPM 13	0.0	0.0	1.3	139.9	0.0
CVPM 14	0.0	0.0	0.0	41.4	0.0
CVPM 15	0.4	0.8	2.9	85.6	0.0
CVPM 16	0.0	0.1	0.1	16.2	0.0
CVPM 17	0.0	0.2	0.4	49.4	0.0
CVPM 18	18.8	0.0	10.0	149.2	0.0
CVPM 19	0.0	0.0	0.0	36.7	0.0
CVPM 20	0.0	0.0	0.0	33.5	0.0
CVPM 21	0.0	0.0	1.4	44.2	0.0
Palo Verde	1.4	6.9	66.1	66.1	66.1
Coachella	0.0	0.9	8.4	8.4	8.4
Imperial	4.3	20.5	105.2	105.2	105.2
North of Delta Ag (R1&2)	6.8	0.0	0.8	824.2	0.0
S. Central Valley Ag (R3&4)	19.1	1.1	17.8	770.5	0.0
So. Cal Ag (R5)	5.8	28.3	179.7	179.7	179.7
Total agriculture	**31.7**	**29.3**	**198.3**	**1774.4**	**179.7**

Table 17. Water scarcity costs for urban economic demand areas ($ million/yr)

Urban demand area	Base 2020	SWM 2020	SWM 2100	PCM 2100	HadCM2 2100
Redding	0.0	0.0	0.0	31.6	0.0
Napa-Solano	22.0	0.0	0.0	0.0	0.0
Contra Costa WD	0.1	0.0	0.0	0.0	0.0
EBMUD	12.5	0.6	3.7	24.1	2.8
Stockton	0.1	0.0	0.0	0.0	0.0
Sacramento	0.0	0.0	0.0	0.0	0.0
Yuba	0.9	0.0	0.0	0.0	0.0
Galt	0.0	0.0	0.0	0.0	0.0
San Francisco	5.1	0.0	2.4	8.8	0.0
Santa Clara Valley	10.2	0.0	0.0	16.0	0.0
Modesto	0.0	0.0	0.0	0.4	0.0
Turlock	0.0	0.0	0.0	1.7	0.0
Merced	0.0	0.0	0.0	0.5	0.0
SB-SLO	0.0	0.0	0.0	0.0	0.0
Fresno	17.7	0.7	0.0	0.2	0.0
Bakersfield	0.0	0.0	0.0	0.0	0.0
Sanger	0.0	0.0	0.0	0.0	0.0
Visalia	0.0	0.0	0.0	5.2	0.0
Delano	0.0	0.0	0.0	3.8	0.0
SBV	3.5	0.0	8.8	8.8	8.8
San Diego	34.7	0.0	150.7	150.7	150.7
East MWD	32.7	0.1	117.9	117.9	117.9
Central MWD	183.4	0.0	170.3	170.3	170.3
Castaic	507.8	2.7	18.9	18.9	18.9
Coachella	367.4	166.2	222.3	222.3	222.3
Mojave	180.7	0.0	45.8	45.8	45.8
Antelope Valley	185.2	0.0	21.1	21.1	21.1
Ventura	0.0	0.0	15.6	15.6	15.6
El Centro	0.0	0.0	4.5	4.5	4.5
Blythe	0.0	0.0	3.5	3.5	3.5
North of Delta Urb (R1&2)	35.5	0.6	3.7	55.7	2.8
S. Central Valley Urb (R3&4)	32.9	0.7	2.4	36.5	0.0
So. Cal Urb (R5)	1,495.6	168.9	779.2	779.3	779.3
Total urban	**1,564.0**	**170.3**	**785.3**	**871.5**	**782.1**

As we will see later, the availability of "backstop" water source technologies, such as wastewater reuse and sea water desalination, dampens the economic ability of water-short urban regions to import additional water. Willingness of urban coastal users to pay for additional imports would be limited by the availability of sea water desalination (at unlimited capacity) at $1,400/acre-ft.

Operations

Figures 17 and 18 show that surface water storage operations vary somewhat among the different model runs, with Base 2020 and HadCM2 2100 runs generally having higher storages and PCM 2100 runs generally having lower surface storages. In Figure 17, the same drought drawdown pattern can be seen for all scenarios (except HadCM2 2100), with a similar seasonal drawdown-refill cycle for all scenarios. As we can see in these figures, the model operates using a 72-year sequence of inflows (based on the historical record), to represent hydrologic variability and various complex expressions of wet and dry years. This is quite important for actual operations and water allocations, as well as for evaluating system performance.

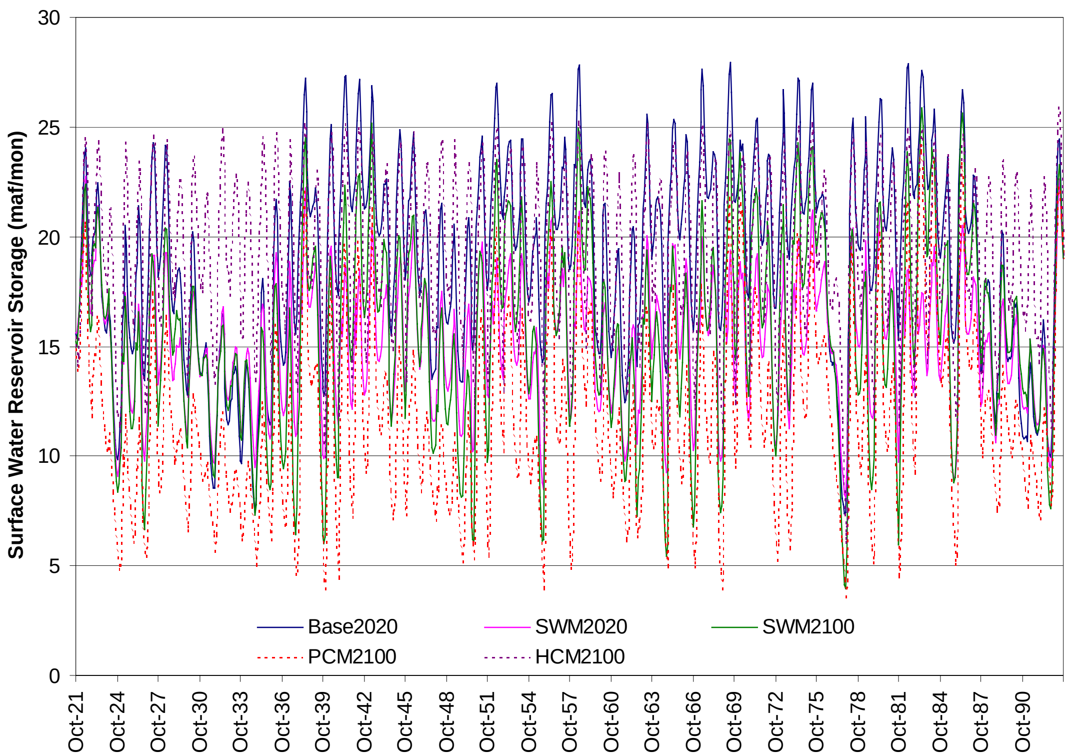

Figure 17. Statewide surface water storage over 72-year period.

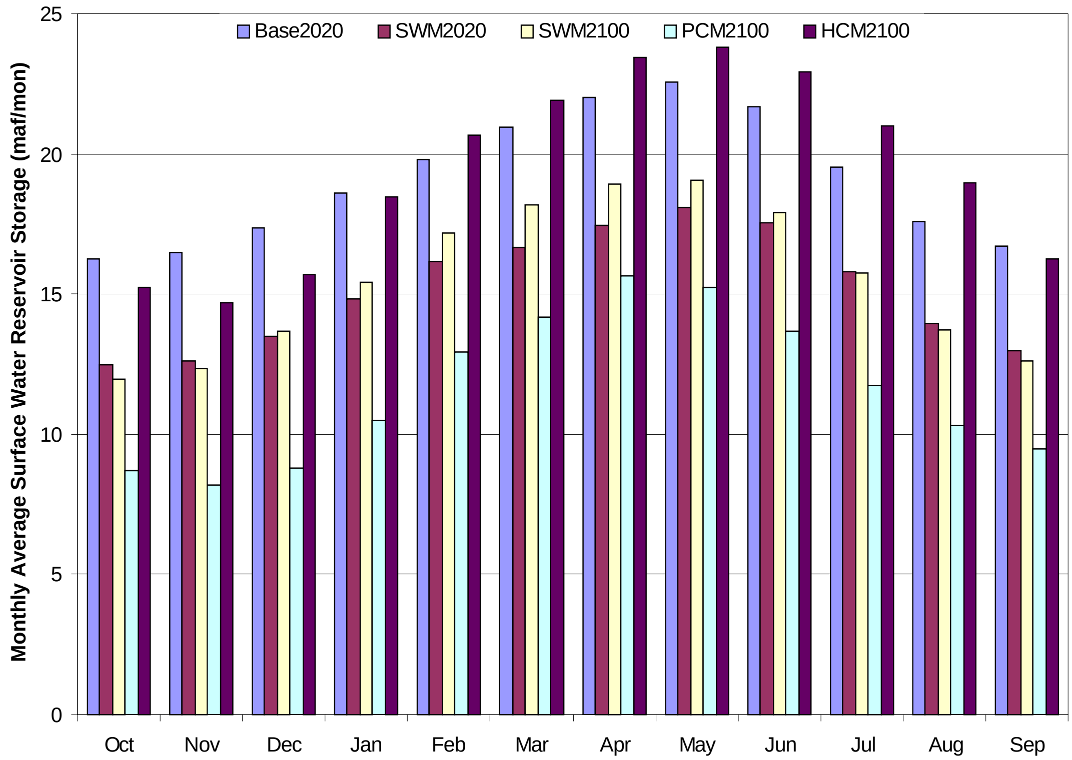

Figure 18. Average seasonal pattern of surface water storage.

The most limiting factor in 2100 is conveyance capacity. This is especially true for Southern California, where present Colorado River Aqueduct and California Aqueduct capacities to deliver water to Los Angeles, San Diego, and other parts of metropolitan Southern California are used to their limits in all 2100 scenarios. This implies that urban users in these regions must be creative about new water supply technologies and water conservation/use efficiency practices. For 2100, Southern California employs considerable quantities of new water supply technology, averaging 1.4 MAF/yr of additional wastewater recycling and 0.2 MAF/yr of sea water desalination. Although these are large contributions by present-day standards, they represent only a modest proportion of Southern California's 2100 urban water demands. Increases in water use efficiency and water conservation are together represented as water scarcity and scarcity cost. These scarcity costs are considerable in 2100 compared with SWM 2100, but they are comparable to Base 2020, or what would be expected if current operation and allocation policies were continued until 2020. In the absence of climate change, flexible operations and allocations provide reasonable water supplies until 2100 for most of California.

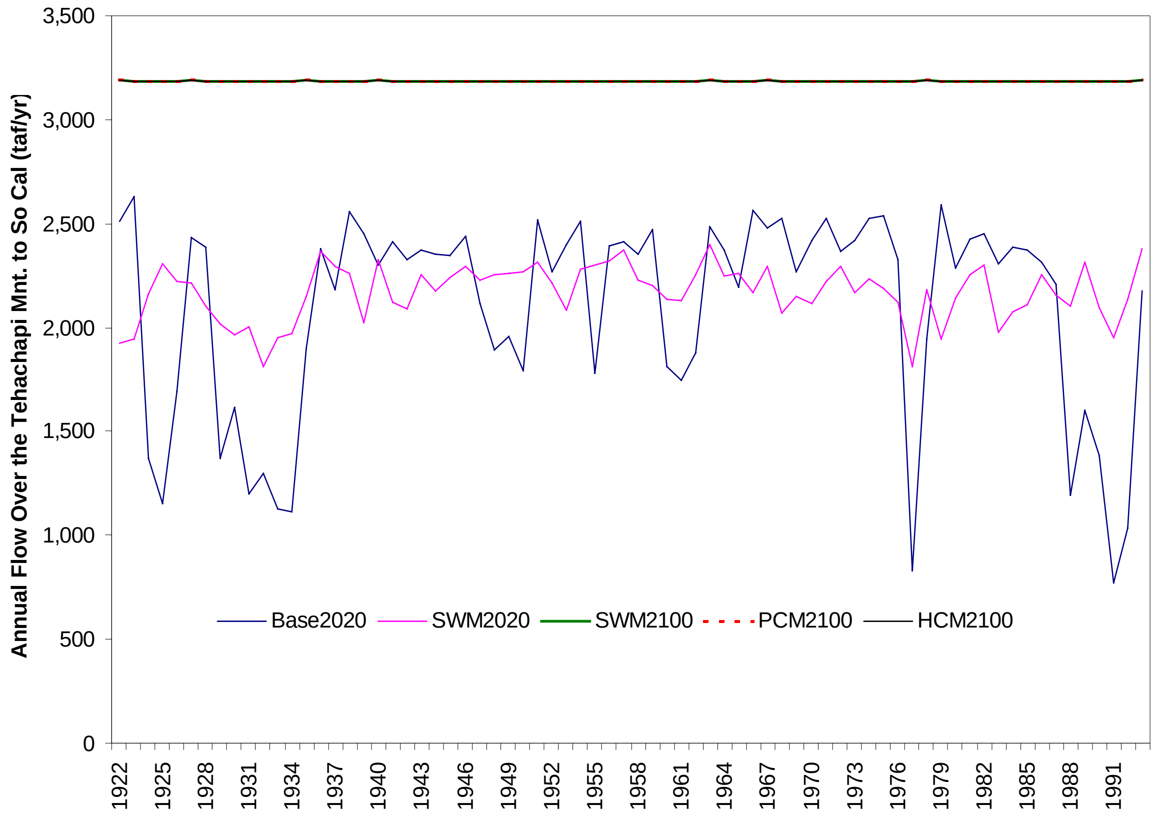

Figure 19. Annual Central Valley imports to Southern California.

Conveyance facilities are among the most binding constraints in the system in the year 2100. Figure 19 shows flows from the State Water Project's California Aqueduct over the Tehachapi Mountains to Southern California. For both 2020 model runs, considerable conveyance capacity remains in this aqueduct; however, for 2100 demands, the aqueduct is always at its capacity for every month of the 72-year period.

Groundwater use

As we can see from comparing the scales of surface water storages and fluctuations in Figure 17 with those for groundwater storage in Figure 20, most water storage capacity in California is underground. Increasing statewide water demands lead to increased use of groundwater storage to even out hydrologic variability. For some decades, most drought storage of water for California users has been underground. In the future, this will increase. Even with current

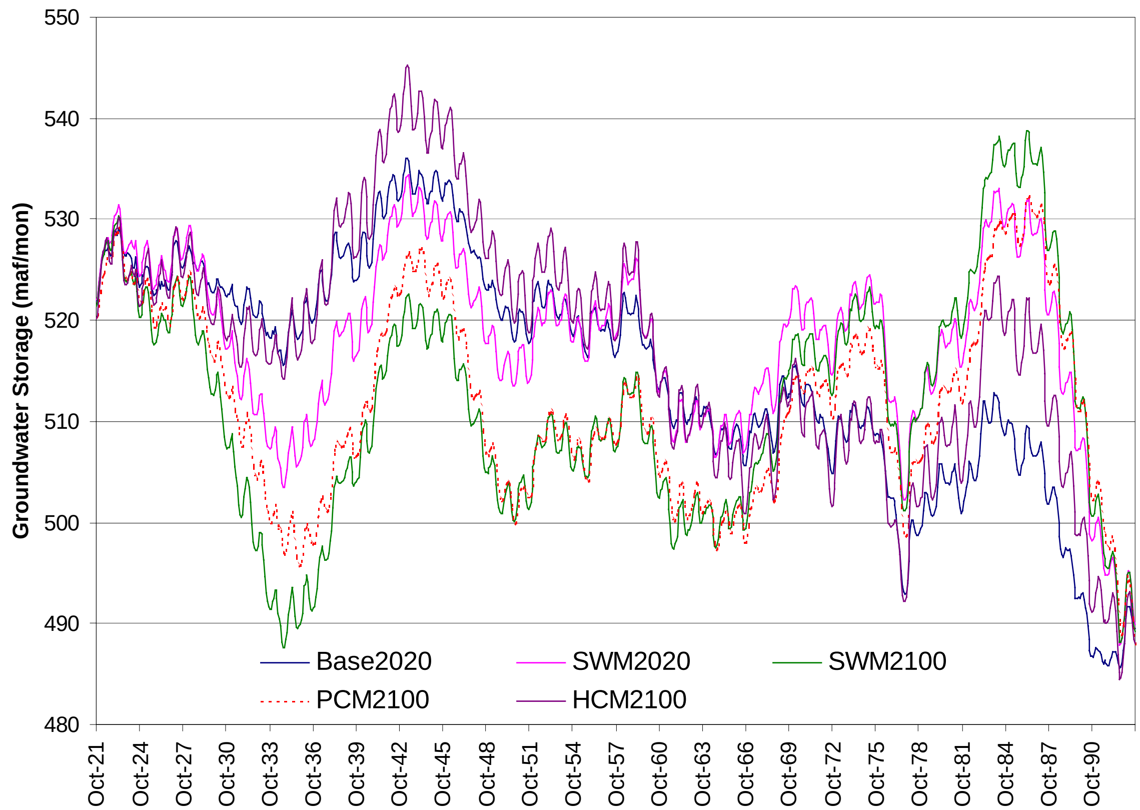

Figure 20. Groundwater storage over the 72-year period.

operating policies, drought storage of water underground amounts to 27 MAF in 2020. With optimized operations in 2020 (SWM 2020), this amount increases only slightly to 45 MAF, but the water is used more aggressively. With continued increases in urban water demands, groundwater used for drought storage increases to about 51 MAF in 2100 (SWM 2100). This represents an expansion in storage far greater than any storage expansions contemplated for surface water storage.

Figure 21 shows that even though the volumetric use of groundwater for drought storage increases with time and urban water demands, the pattern of use remains similar with time. There is some slight increase in dependence on groundwater with time, but the major change is the evolution of operating policies from current policies (Base 2020) to more economic operations (SWM 2020). Thereafter, the pattern of using groundwater more explicitly for drought storage remains clear and relatively constant.

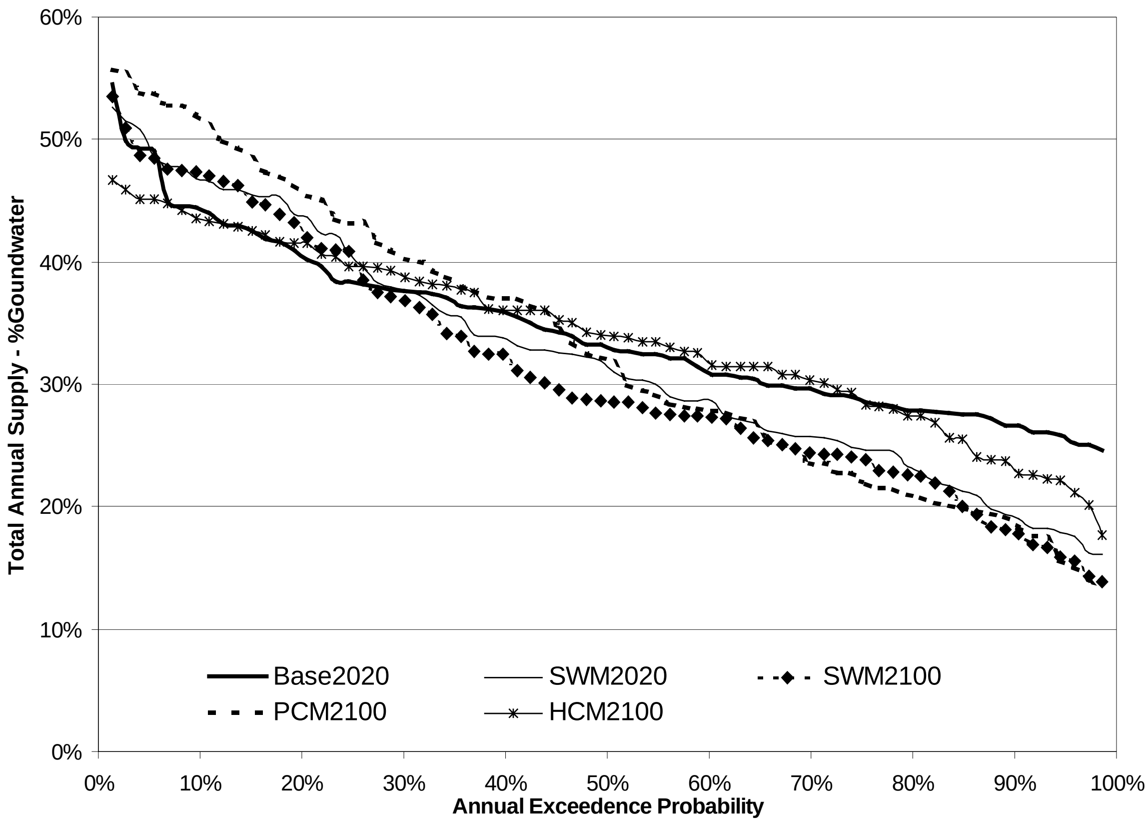

Figure 21. Annual variability in statewide use of groundwater.

Although the qualitative nature of these groundwater findings would seem to make them fairly secure, precise results are less certain, given the poor data available for representing groundwater and groundwater operations in models of California water (Jenkins et al., 2001).

New water management technologies

For any climate warming scenario, increasing urban water demands, without an associated expansion of the conveyance capacity, lead to the increased use of new water supply technologies in 2100. This is particularly true for Southern California, which in our model runs is limited to the existing conveyance capacity for importing additional water from outside its urban areas.

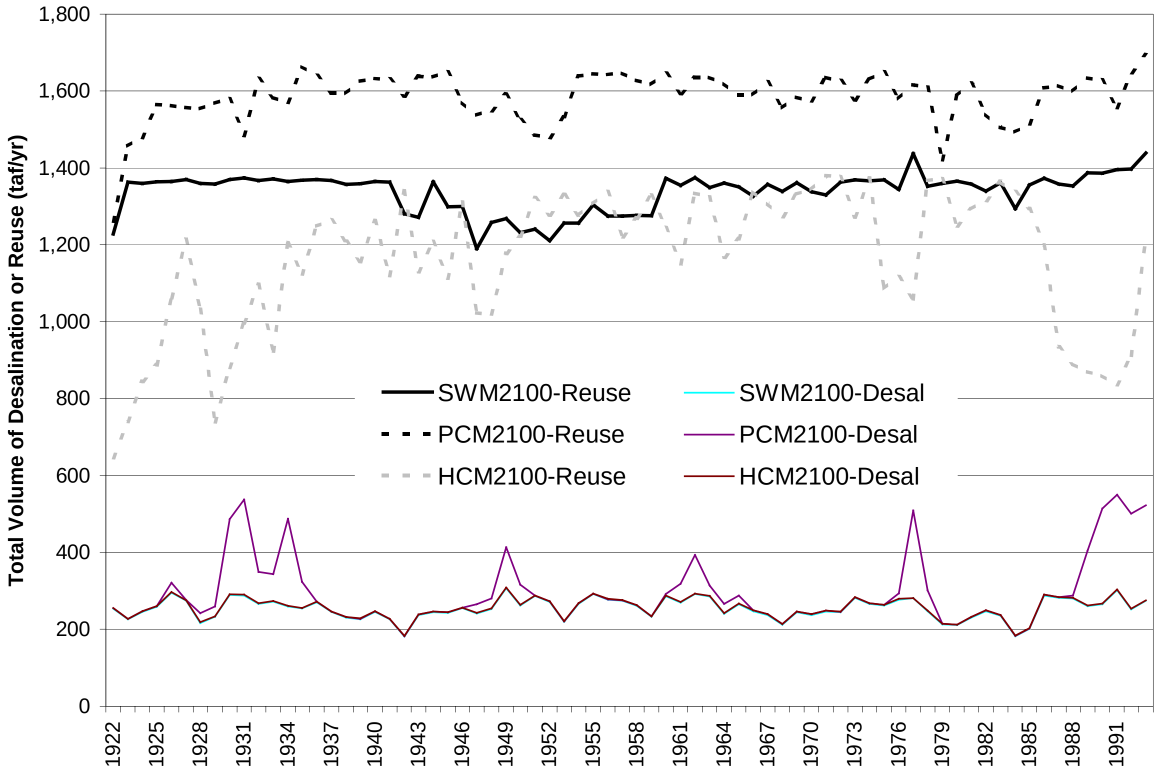

Figure 22. Use of seawater desalination and urban wastewater recycling in 2100.

Figure 22 illustrates the increased employment of wastewater reuse and sea water desalination for the three 2100 climate scenarios. Use of both new water supply technologies increases greatly, with somewhat greater application of both technologies occurring under the PCM 2100 hydrology. About 240 TAF/yr of sea water desalination is employed, somewhat more with PCM 2100 hydrology (at \$1,400/acre-ft or \$1.15/m^3). Urban wastewater reuse is employed at about 1,350 TAF/yr (1,600 TAF/yr for PCM 2100) above 2020 reuse levels (at \$1,000/acre-ft).

Environmental performance and opportunity costs

Table 18 gives the shadow costs of various environmental flows to agricultural, urban, and hydropower users for the four optimized scenarios. Shadow costs are the cost to the economic values of the system (urban, agricultural, hydropower, and operations) of a unit change in a constraint, in this case environmental flow requirements. The effects of population increase (and

Table 18. Shadow costs of environmental requirements

	Average WTP ($/acre-ft)			
Minimum instream flows	**SWM 2020[a]**	**SWM 2100**	**PCM 2100**	**HadCM2 2100**
Trinity River	0.6	45.4	1,010.9	28.9
Clear Creek	0.4	18.7	692.0	15.1
Sacramento River	0.2	1.2	25.3	0.0
Sacramento River at Keswick	0.1	3.9	665.2	3.2
Feather River	0.1	1.6	35.5	0.5
American River	0.0	4.1	42.3	1.0
Mokelumne River	0.1	20.7	332.0	0.0
Calaveras River	0.0	0.0	0.0	0.0
Yuba River	0.0	0.0	1.6	1.0
Stanislaus River	1.1	6.1	64.1	0.0
Tuolumne River	0.5	5.6	55.4	0.0
Merced River	0.7	16.9	70.0	1.2
Mono Lake inflows	819.0	1,254.5	1,301.0	63.9
Owens Lake dust mitigation	610.4	1,019.1	1,046.1	2.5
Refuges				
Sacramento West Refuge	0.3	11.1	231.0	0.1
Sacramento East Refuge	0.1	0.8	4.4	0.5
Volta Refuges	18.6	38.2	310.9	20.6
San Joaquin/Mendota refuges	14.7	32.6	249.7	10.6
Pixley	24.8	50.6	339.5	12.3
Kern	33.4	57.0	376.9	35.9
Delta outflow				
Delta	0.1	9.7	228.9	0.0

a. SWM 2100 results do not include hydropower values (except for Mono and Owens flows).

the addition of hydropower) are substantial, and would somewhat increase the economic basis for controversy about environmental flows. The increase in shadow costs from SWM 2020 to SWM 2100 is not overwhelming (especially considering that including hydropower in SWM 2020 would raise some costs for that scenario).

Table 19. Infeasible environmental requirements under PCM 2100 hydrology

Flow location	Current requirements (TAF/yr)	Average reduction (TAF/yr)		
		SWM 2100	PCM 2100	HadCM2 2100
Trinity River	599	No change	1.1	No change
Sacramento River at Keswick	4,069	No change	112.3	8.43
Clear Creek	122	No change	11.1	No change
Sacramento River (various locations)	2,000-3,000	No change	36.9	No change
Sacramento Naval Control Point	3,293	No change	20.3	No change
American River downstream of Nimbus	1,398	No change	0.6	No change
Mono Lake inflow	74	No change	10.6	No change
Mono Lake minimum storage	-	No change	Removed	No change
Total		No change	**328.7**	**8.4**

Adding the dry PCM 2100 hydrology to the high population in SWM 2100 creates a very substantial increase in the agricultural, urban, and hydropower costs of environmental flows. In most cases, the shadow costs of environmental flows are increased by at least an order of magnitude to very substantial absolute amounts. The dry PCM 2100 form of climate warming would add substantial additional stress and controversy to environmental flows.

In some cases, the PCM 2100 hydrology is infeasibly dry for some environmental flows. This hydrology simply does not have enough water in some parts of the system at some times to satisfy current environmental requirements, even if all water were allocated for environmental uses. These infeasibilities, which are noted in Table 19, required modest reductions in some environmental flows. In the case of Mono Lake, for the dry PCM 2100 scenario, the minimum storage constraint was eliminated; SWM 2100 Mono Lake storage is 3.2 MAF. For PCM 2100, the Mono Lake storage is 2.7 MAF. In contrast, the wet HadCM2 2100 hydrology is more benign than the historical hydrology in terms of the economic effects of environmental flows. For this scenario, many shadow costs disappear or are greatly diminished in importance.

The average shadow costs in Table 18 vary considerably by month and between wet and dry years. This is illustrated dramatically in Figure 23, which is a plot of the shadow costs of Trinity River instream flow requirements over time. Here, the differences in the average shadow costs for the different scenarios are very evident, but considerable seasonal and interannual variability is also evident. In wet years, environmental requirements can incur far lower than average costs, and in dry years these shadow costs can be considerably higher. This hints that there might be

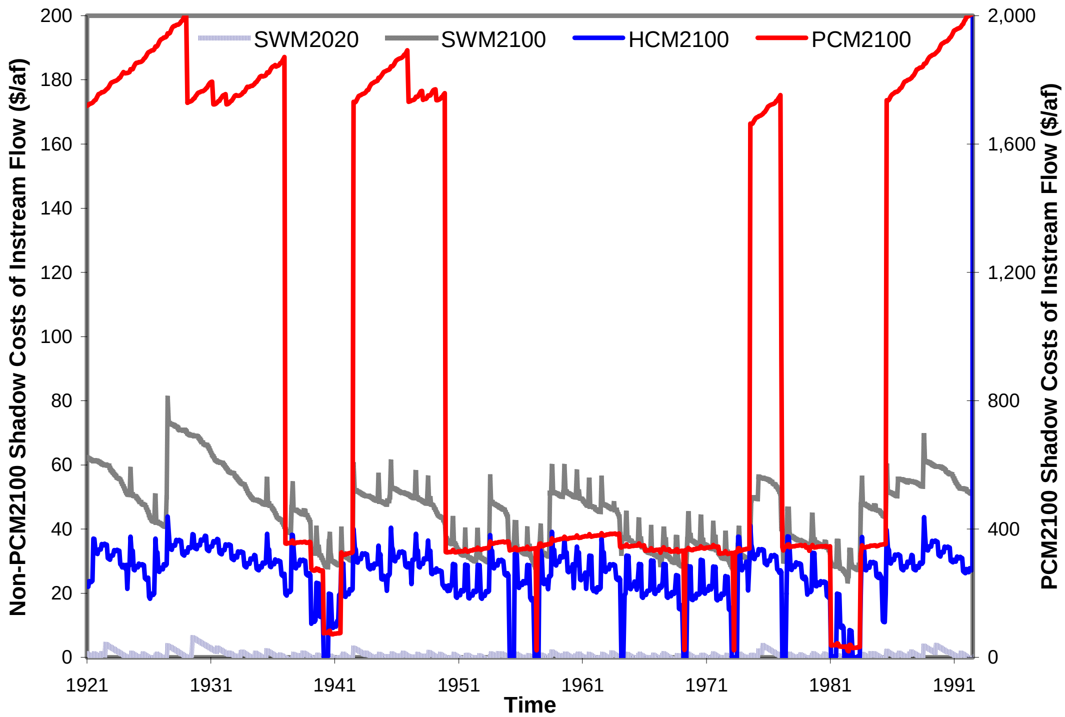

Figure 23. Time series of shadow costs for Trinity River outflow requirement.

opportunities for more flexible forms of environmental regulation that could be mutually beneficial to environmental and economic water users. The high costs of Trinity River environmental flows in the PCM 2100 run arise from high economic costs of scarcity in the Redding metropolitan area.

Figure 24 offers similar insights from seasonal variability on shadow costs for delta outflow requirements. In the case of delta outflows, PCM 2100 greatly reduces surplus delta outflows (see Figures 25 and 26), both in magnitude and frequency, as well as increasing the shadow costs of minimum flows.

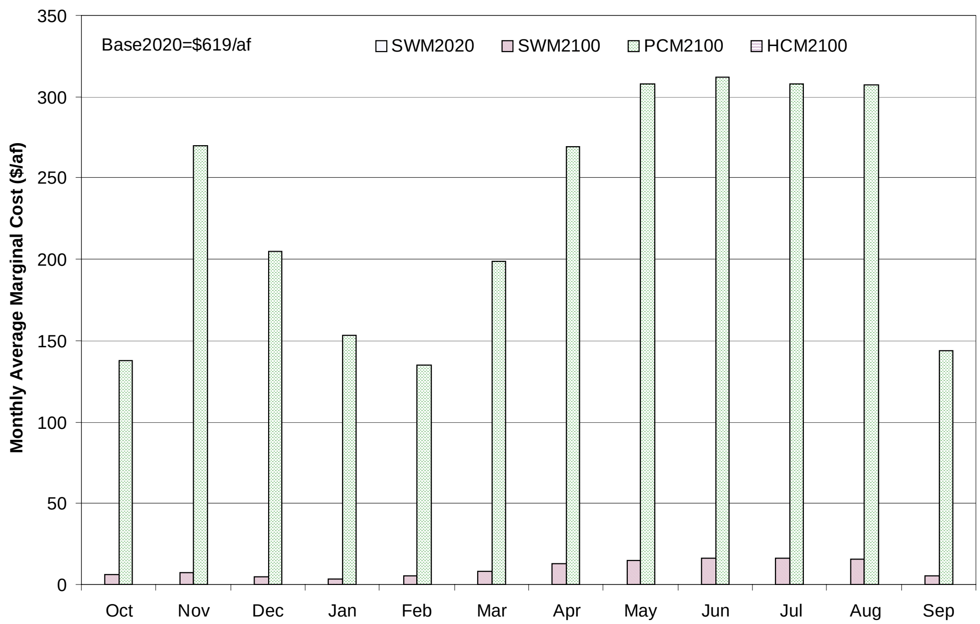

Figure 24. Opportunity (shadow) costs of delta outflow requirements for agricultural and urban users: Monthly averages.

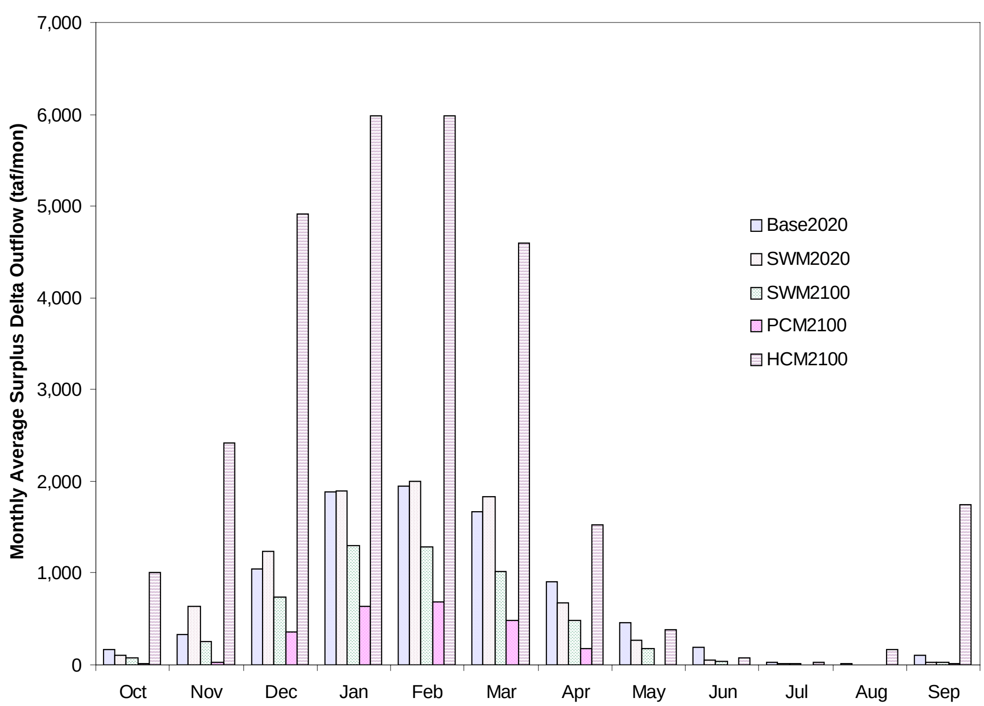

Figure 25. Monthly average surplus delta outflows.

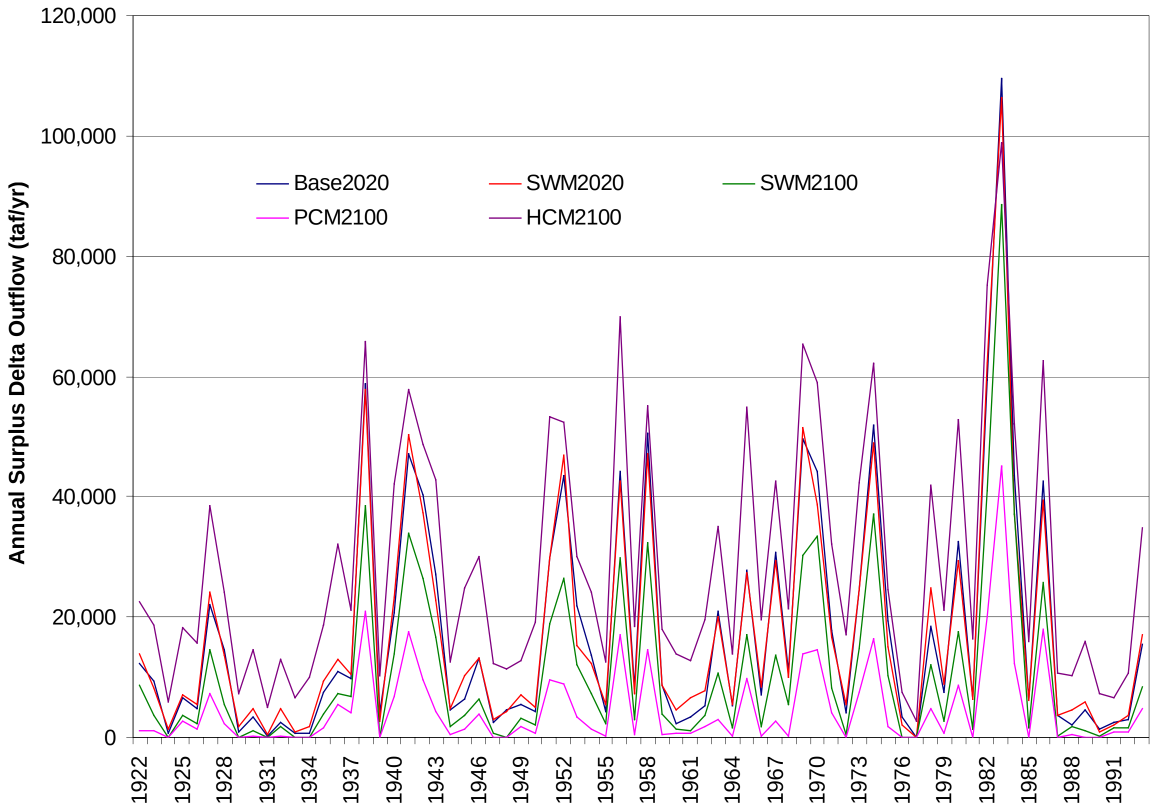

Figure 26. Annual surplus delta outflow.

Flood flows

Climate warming's effects of depriving California's hydrology of the storage capacity of snowpacks, both for buffering floods and providing seasonal water supply storage, has long been a concern. Although flood damages are not explicitly represented in this model, flood flows and frequencies are apparent in the model results. Two examples of flood results from the three modeled hydrologies appear in Figures 27 and 28. In both cases, the dry warming PCM hydrology does not show a substantially greater flooding threat. This conclusion is somewhat tentative given the monthly basis of the model and the lack of explicit flood penalties in the model. However, the curves demonstrate that for the PCM 2100 hydrology, monthly flows at several especially vulnerable geographic locations do not seem greater, and are often much less than managed flows with the historical hydrology.

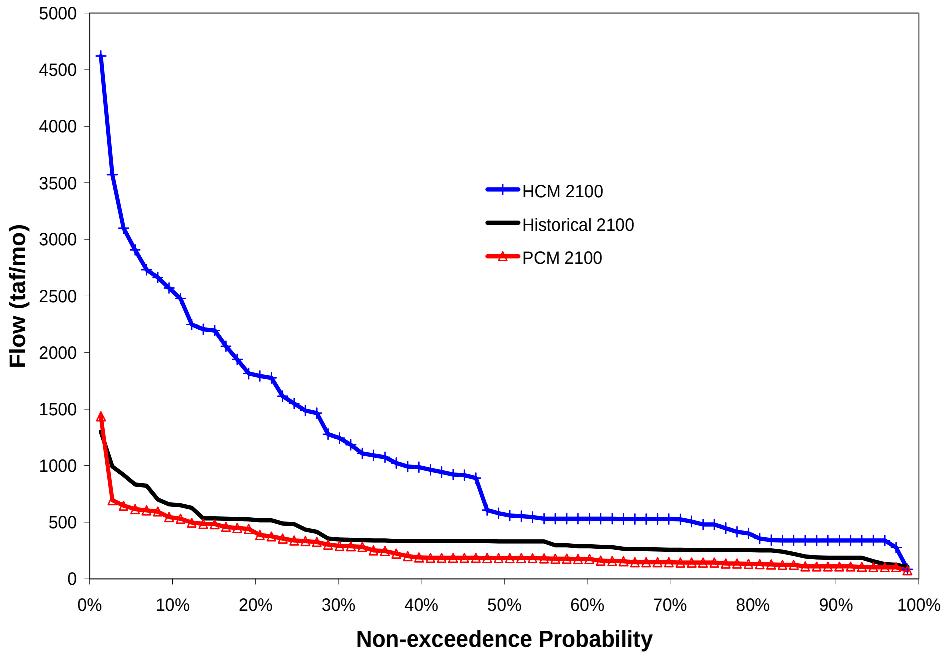

Figure 27. Annual flood probabilities: American River.

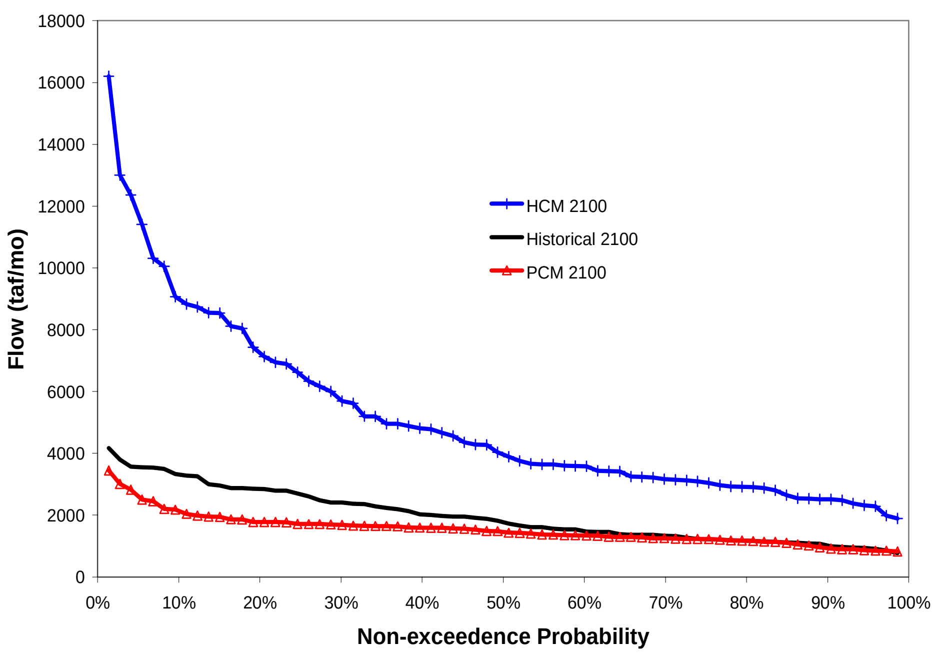

Figure 28. Annual flood probabilities: Sacramento River upstream of confluence with American River.

However, wet forms of climate warming could be devastating, as shown for the HadCM2 2100 hydrology at these two critical locations. Monthly flood flows are tremendously greater than anything experienced historically. Given the magnitude of these flood flows relative to current or even imaginable flood storage capacity on these rivers, it is unlikely that flood storage in surface reservoirs would contain flood peaks. Monthly flows for many events on the American River are well above current levels. For the Sacramento River above the confluence with the American River, increases in flood flows could be greater still. In both cases, increased flood volumes could easily be above those controllable by current or potential surface water reservoirs.

These startling flooding results might be something of an artifact of the hydrology used for this and most other climate change projects; by changing each flow in the historic record by a constant monthly percentage to represent climate warming seen in a short record of GCM results on a few basins, peak flows might be over- or underestimated. This merits further hydrologic and operational research, perhaps using a different set of permutations for different year types for the GCM scenarios. The general magnitude of flood flow frequency changes after reservoir operation is not greatly different from that found for inflows before reservoir operations (Miller et al., 2002). Flood flow frequency and adaptation studies for the Lower American River (Zhu et al., 2003), based on the same HadCM2 2100 hydrology (Miller et al., 2001), show serious, but not so overwhelming, results. Additional flood studies for long-term urbanization and climate change are likely to be desirable, given the long-term nature of land use changes and flood control infrastructure decisions.

Value of expanded storage and conveyance facilities

Table 20 contains the average marginal values of increased capacity for various selected storage and conveyance capacities in California's water system for the 2100 scenarios. All of these values are greater than those for 2020 populations (Jenkins et al., 2001), reflecting increasing water demands throughout the intervening 80 years. For all scenarios, expanding conveyance facilities typically has much greater value than expanding reservoir storage capacities.

Hydropower performance

The model produced estimates of hydropower generation and economic value for the major water supply reservoirs in the California system. Although these do not include all the reservoirs of importance to hydropower in the system, they do include the major reservoirs where trade-offs exist between hydropower and water supply operations.

Hydropower production from the major water supply reservoirs in the California system would not be greatly affected by population growth, but would be reduced by the PCM 2100 climate warming scenario. Base 2020 hydropower revenues average $161 million/yr from the major water supply reservoirs, compared with $163 million/yr for SWM 2100. However, the dry PCM

Table 20. Average marginal value of expanding selected facilities (shadow values)

	Average marginal value ($/unit-year)		
Facility	**SWM 2100**	**PCM 2100**	**HadCM2 2100**
Surface Reservoir (TAF)			
Turlock Reservoir	69	202	56
Santa Clara aggregate	69	202	56
Pardee Reservoir	68	202	56
Pine Flat Reservoir	66	198	56
New Hogan Lake	66	198	56
New Bullards Bar Reservoir	65	196	56
Los Vaqueros Reservoir	64	186	53
Lake Success	32	150	22
Lake Eleanor	28	125	21
Lake Mathews (MWDSC)	28	125	21
Lake Kaweah	28	124	21
Conveyance (TAF/month)			
Lower Cherry Creek aqueduct	7,886	8,144	7,025
All American Canal	7,379	7,613	6,528
Los Vaqueros delivery to Contra Costa Canal	7,379	7,613	6,528
Putah South Canal	7,378	7,611	6,528
Mokelumne Aqueduct	7,180	7,609	6,301
Coachella Canal	3,804	3,487	3,618
Friant Kern Canal	1,733	1,960	3,585
San Diego Canal	1,289	1,196	985
Colorado Aqueduct	1,063	970	759
California Aqueduct	669	1,823	452
Contra Costa Canal	519	543	373
Hetch Hetchy Aqueduct	489	410	452

2100 scenario reduces hydropower revenue 30% to $112 million/yr. Even though this does not include the hydropower impacts of climate change on other hydropower plants in California, the percentage of reduction is probably reasonable overall. With the wet HadCM2 2100 hydrology, hydropower production greatly exceeds current levels ($248 million/yr). Figures 29 through 31 depict seasonal and interannual variability in hydropower generation and economic value.

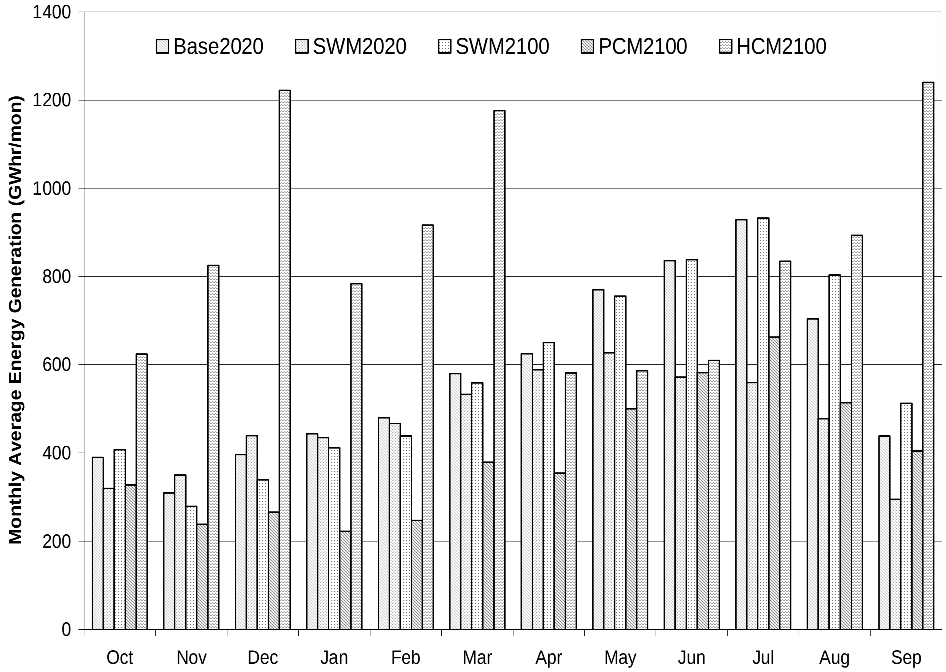

Figure 29. Monthly hydropower generation from major reservoirs.

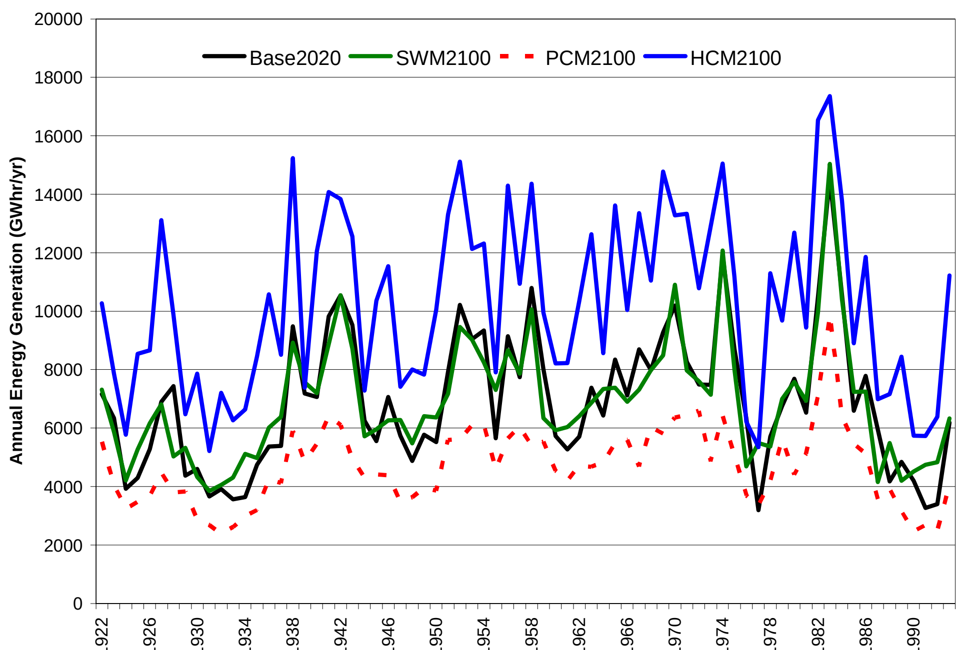

Figure 30. Annual hydropower generation from major reservoirs.

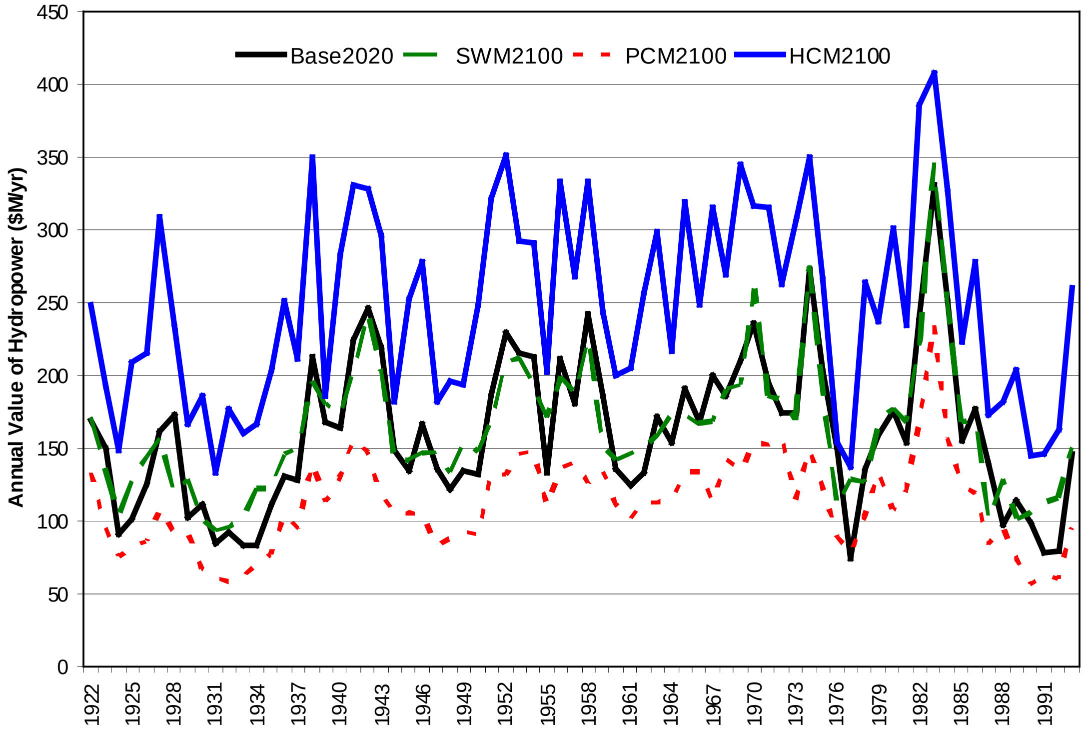

Figure 31. Annual hydropower value for major reservoirs changes in agricultural acreage and income.

Changes in agricultural acreage and income

Figure 32 shows changes in water use, irrigated acreage, and farm income between SWM 2100 and PCM 2100 for 21 agricultural regions in the Central Valley. These results come from postprocessing the agricultural water deliveries from the CALVIN model runs through the more detailed SWAP model of Central Valley agricultural production and economic value.

These model results illustrate the additional adaptive responses that farmers can take to climate and water delivery changes. Although water deliveries are greatly reduced in many cases for the PCM 2100 scenario, acres irrigated are reduced much less. And because farmers shift to higher valued crops, agricultural income reductions are much less still, averaging about 6% statewide despite about 24% reduction in agricultural water deliveries, with about 15% reduction in irrigated land.

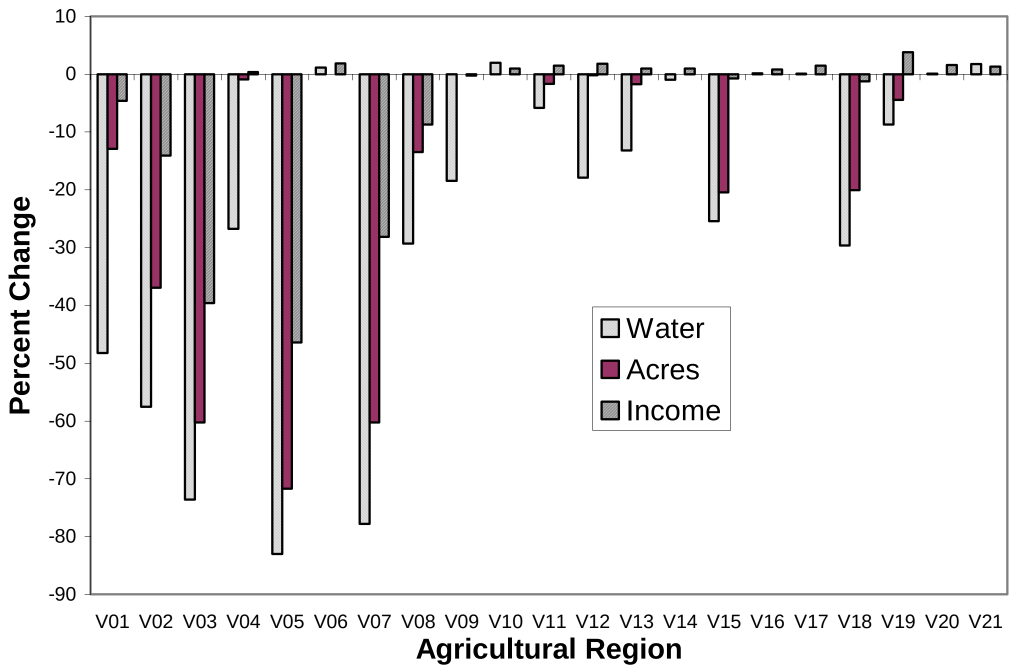

Figure 32. SWM2100 — PCM2100 changes in agricultural water, acreage, and income by Central Valley agricultural region.

Large complex systems tend to have many layers of potential adaptation. In the case of California water, adaptation layers at state, regional, local, and user levels can provide a substantial level of buffering for climate warming impacts. However, if these layers are to be effective, they must be allowed and encouraged to function appropriately.

5. Conclusions

If anything is clear, it is that the future is unclear. California has always changed in a number of ways, and such changes will continue. The state's water management system has always been both a cause and a result of other changes within its borders.

5.1 Some Questions Answered

What are some major changes that can be expected in California by 2100?

- Climate warming could easily be a significant force in the future. Some hydrologic indications of climate warming have already been seen in California (Aguado et al., 1992; Dettinger and Cayan, 1995).
- Sea level rise is fairly certain.
- Other changes in climate, including changes in climate variability, are possible, although we know less about them. Several types of climate variability seem present in the historical record and in contemporary climate processes.
- Population growth and technological changes are more certain, with implications for urban and agricultural land uses and water demands. Increases in household wealth may further increase water demands.
- Water use, reuse, and management technologies will improve, and show increased promise for the future, particularly in the absence of major conveyance facility expansions.
- Changes in water quality regulations are likely to be important.
- There will be incentives for change in management and institutions governing California water.

What would be the major hydrologic effects of climate warming?

- Winter streamflows generally will increase, with prospects for increased flooding. For wetter forms of climate warming, these effects might be large enough to overcome regulation by current or plausibly sized proposed reservoirs.
- Spring snowmelt runoff will decrease, challenging water supply operations.
- Continued or accelerated sea level rise will threaten islands and water quality in the San Francisco and San Joaquin Delta.
- Higher precipitation rates could substantially reduce or overcome effects of reduced snowpack on water supply.

- It is unclear if climate warming will increase or decrease total water availability for California.

Overall, climate warming could have either negative or positive effects on California's ability to supply water for urban, agricultural, and environmental purposes. However, it appears most likely that the depletion of snowpack and spring runoff would lessen the performance of the state's water supply system, at a time of major growth in high-valued urban water demands.

How could California's water system adapt to expected changes in 2100, including climate warming and 200% population growth?

California has a tremendously versatile natural and human-made water management system. It has a large capacity to adapt, by making improvements in the conjunctive use of ground- and surface waters, water markets, transfers and exchanges, urban wastewater reuse, sea water desalination, and water use efficiency. This capacity to adapt may be considerable, but it is not an infinite or perfect ability to adapt to huge changes. Scarcities of water are likely to occur at some locations and times, and it is sometimes more expensive to supply additional water than to accept some water scarcity. Some scarcity can be optimal, but there is also considerable value to be gained by expanding some facilities, particularly conveyance. Most of these changes are desirable with or without changes in climate, and are driven solely by growth in water demands.

Could California's water system adapt to these anticipated growth and climate warming changes?

California's water system could economically adapt to the range of climate warming scenarios examined. In the most extreme dry scenarios for climate warming, the Central Valley's agricultural sector would be severely affected. The costs and damages from severely dry climate warming would be significant, on the order of the current revenues for California's largest water district (about $1 billion). But on a state- and economy-wide basis, these water supply and hydropower costs are not large. California's current state budget is almost $100 billion/yr and its gross domestic product is about $1.3 trillion/yr.

What are the most promising adaptations for California's water management system to respond to severely dry forms of climate warming?

For the severely dry PCM 2100 climate warming scenario, the optimization model results suggest:

- Conjunctive use of ground- and surface waters to cover storage is very promising economically.

- Selling water from agriculture to urban areas could compensate economically for lesser amounts of available water.

- Fallowing of agricultural land results from lesser water availability and lower water sales.

- Some facility expansions, particularly for conveyance and for wastewater reuse, appear economically promising.

These same responses are also promising, although to lesser degrees, for historical hydrology and the warm wet HadCM2 hydrology. These actions, and the required institutional changes needed to support then, would constitute a potential "no regrets" strategy (Stakhiv, 1998).

What would be the greatest problems brought to California by severely dry climate warming?

- Central Valley agriculture could be devastated by severely dry forms of climate warming. Some Central Valley regions would lose or sell on the order of half their desired water use levels.

- Environmental water uses become vastly more expensive in terms of their effects on agricultural, urban, and hydropower economic performance. This would tend to greatly increase the controversy about water management in California.

- Southern California urban users, who are largely isolated from the system by limited conveyance capacity and have very high willingness to pay for water, would be much less affected by climate change. However, Southern California users are acutely affected by population growth.

How would climate warming affect the lives of future Californians?

Even after conducting such sophisticated modeling work, we can really only speculate:

- Urban water users would see much higher costs for water supply. Although expensive, these costs would pay for fairly reliable supplies and involve more use of newer wastewater reuse, desalination, and water use efficiency technologies.

- Central Valley agriculture is rather unsheltered from positive or negative effects of climate warming on water supplies. Some financial buffering for farm owners exists from potentially lucrative sales of water to cities, particularly in dry climate warming scenarios.

- Flooding effects could be very substantial with wet forms of climate warming. These flooding effects could be beyond the management capabilities of existing or plausible new reservoirs. In this case, expanding floodways and making large changes in floodplain land use might become desirable.

- Drier climate warming scenarios greatly increase the likelihood and severity of economically motivated conflicts about environmental water allocations. Under drier scenarios, the system as a whole must be more tightly managed with greater consequences for all users, but especially agricultural and environmental users. Conversely, wetter climate warming greatly reduces the frequency and severity of trade-offs and potential conflicts among water supply users.

- Climate warming, of any form, would create incentives for changes in how California's water is managed.

What potentially big effects were not considered in this study?

Many factors cannot be considered in any real and finite analysis; some missing considerations that are likely to be important are

- We did not explicitly consider flood damages and adaptation to floods in these model runs. For wet forms of warming, these effects are likely to be considerable. Zhu et al. (2003) describe some very preliminary results for the Lower American River, based on the HadCM2 hydrology used in this study.

- Because we did not account for the urbanization of agricultural land in the Central Valley in the model runs, modeled Central Valley agricultural water demands are about 2 MAF/yr too high. Even though this is a large quantity of water, it is not enough to change the report's qualitative conclusions; Central Valley agriculture would remain tremendously affected under the PCM 2100 hydrology and relatively unaffected for the historical and HadCM2 2100 hydrologies.

- Nonpopulation effects on water demands were largely omitted from this study. Urban demands could be larger because of increased wealth or smaller because of improvements in water use efficiency. Agricultural water demands could be larger or smaller as a result of changes in prices and demands for agricultural products and technological or climatic changes in agricultural yields, and could be smaller as a result of increased real costs of agricultural production accruing from the environmental impacts of agriculture.

- We took delta salinity and other water quality requirements from the DWR's 2020 modeling studies. Recent preliminary postprocessing of the CALVIN PCM 2100 results through the DWR hydrodynamic model of delta salinity indicates problems with salinity intrusion in winter months, although this might also be an artifact of assumed in-delta operations. Mode examination of this issue is desirable, perhaps in conjunction with considering the effects of sea level rise.

- These results are sensitive to large reductions in costs for sea water desalination or wastewater reuse. Based on the costs of alternative sources of water, if costs of desalination or reuse were reduced to $500-$800/acre-ft, these newer technologies could economically displace some traditional supplies for coastal and urban areas. Some results are also likely to be sensitive to the availability of conveyance and groundwater recharge capacity, as indicated by shadow values on facility capacities.

- Climate changes other than warming might prove significant. Sea level rise effects on delta exports and agriculture are likely to be important. Climate variability and changes in this variability, although currently difficult to represent for analytical purposes, could be substantial.

- Here, we assumed that California's water management institutions could adapt to population growth and climate changes gracefully and effectively. However, although water management institutions can certainly adapt to changes in conditions, they may do so more slowly and imperfectly.

5.2 Overall Study Conclusions

The main conclusions of this work are

- Methodologically, it is possible, reasonable, and desirable to include a wider range of hydrologic effects, changes in population and water demands, and changes in system operations and management in impact and adaptation studies of climate change than has been customary. Overall, including such aspects in climate change studies yields more useful and realistic results for policy, planning, and public education purposes.

- A wide range of climate warming scenarios for California shows significant increases in wet season flows and significant decreases in spring snowmelt. For California's major water sources, we can draw this conclusion, which confirms many earlier studies, more generally and quantitatively. The magnitude of climate warming's effect on water supplies can be comparable to water demand increases from population growth in the coming century. We did not examine other forms of climate change, such as sea level rise.

- California's water system can adapt to the population growth and climate changes modeled, which are fairly severe. This adaptation will be costly in absolute terms, but, if properly managed, should not threaten the fundamental prosperity of California's economy or society (although it can have major effects on the agricultural sector). The water management costs are a tiny proportion of California's current economy.

- Agricultural water users in the Central Valley are the most vulnerable to climate warming. Wetter hydrologies could increase water availability for these users, but the driest climate warming hydrology would reduce agricultural water deliveries in the Central Valley by about one-third. Some losses to the agricultural community in the dry scenario would be offset by water sales to urban areas, but much of this loss would be an uncompensated structural change in the agricultural sector.

- The balance of climate warming effects on agricultural yield and water use is unclear. Although higher temperatures can be expected to increase evapotranspiration, longer growing seasons and higher carbon dioxide concentrations can be expected to increase crop yields. The net effect is likely to be an increase in crop yields per unit of water.

- Water use in Southern California is likely to become predominantly urban in this century, with Colorado River water now used for agricultural purposes being displaced by urban growth and diverted to serve urban uses. This diversion is limited only by conveyance capacity constraints on the Colorado River Aqueduct deliveries of Colorado River water and California Aqueduct deliveries of water from the Central Valley. Given the small proportion of local supplies in southern California, the high willingness to pay of urban users, and the conveyance-limited nature of water imports, this region is little affected by climate warming. Indeed, even in the dry scenario, Southern California cannot seek additional water imports. Population growth, conveyance limits on imports, and high economic values lead to high levels of wastewater reuse and lesser but substantial use of sea water desalination along the coast.

- Flooding problems could be formidable under some wet warming climate scenarios. Flood flows indicated by the HadCM2 2100 scenario would be well beyond the control capability of existing, proposed, and probably even plausible reservoir capacities. In such cases, major expansions of downstream floodways and changes in floodplain land uses might become desirable.

- Although adaptation can be successful overall, the challenges are formidable. Even with new technologies for water supply, treatment, and use efficiency; widespread implementation of water transfers and conjunctive use; coordinated operation of reservoirs; improved flow forecasting; and the close cooperation of local, regional, state, and federal government; the costs will be high and there will be much less "slack" in the system compared to current operations and expectations. The economic implications of water management controversies will be greater, motivating greater intensity in water conflicts, unless management institutions can devise more efficient and flexible mechanisms and configurations for managing water in the coming century.

- The limitations of this kind of study are considerable, but the qualitative implications seem clear. It behooves us to carefully consider and develop a variety of promising infrastructure, management, and governance options to allow California's local, regional, and statewide water systems to respond more effectively to major challenges of all sorts in the future.

5.3 Further Research

We can make a number of recommendations for future study:

- Improvements to the base CALVIN model, detailed in Chapter 5 of Jenkins et al. (2001), are desirable for many purposes. Especially advantageous improvements include representation and hydrology in the Tulare Basin and the ability to operate with lower levels of hydrologic foresight. Improved representation of groundwater recharge, operations, and quality in many parts of California would also be beneficial.

- The effects of sea level rise on water availability through the Sacramento-San Joaquin Delta are potentially of great importance. These could not be included in this study, but merit further examination. As part of such work, improved delta outflow water quality requirements for 2100 conditions and hydrologies should be developed.

- For climate change studies in particular, including flood damages and explicitly incorporating agronomic and land use effects on economic values of water deliveries for agriculture would be useful. In this study, we collected data for such improvements, but were unable to incorporate them into the model in time for the project's completion.

- Modeling of flood flow impacts, responses, and adaptations is likely to be very important for wet climate warming scenarios. Given the potential magnitude of these flooding impacts, land use changes and adaptations and their economics should be incorporated explicitly. Some other non-CALVIN modeling results for climate warming and flooding on the Lower American River (Zhu et al., 2003), give a more refined but still preliminary look at this problem.

- In this work, we examined only some forms of climate warming and their effects on the long-term management of California water. In addition to sea level rise, there is evidence of significant long-term variability in California's climate, not necessarily related to climate warming. These and other reasonable climate change scenarios should be considered for additional operational studies.

- Hydrology development for this work was based on permutation ratios that varied by month for each stream in the modeled system. For the GCM scenarios, it might be valuable to develop more complex hydrologies, where these permutation ratios vary with year type (e.g., wet, dry, and intermediate years). This might show some effects on drought and flood behavior. Running additional hydrologies through the management model would allow intermediate and perhaps more extreme climate change scenarios to be assessed.

- Additional postprocessing of results would reveal impacts and promising adaptations in more detail.

- Additional index basins and improvements in deep percolation and reservoir evaporation representations would help to refine hydrologic estimates of climate warming. In doing so, consideration should be given to altering flows by year types, instead of having all years altered by the same monthly factors. If wet and dry years are changed differently with a climate change scenario, it is important to try to preserve such changes when going from GCM results to hydrologic inputs for distributed operations models.

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Appendix VII — Attachment A

Climate Change Surface and Groundwater Hydrologies for Modeling Water Supply Management

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Abstract

Global warming has significant impacts on hydrologic processes in terms of water availability and quality. Several studies have been done on California's hydrologic response to climate change. Most studies indicate that California may have more winter runoff and less summer runoff throughout the next century. However, almost all these studies focus exclusively on changes in streamflow in a few rivers. Based on projected streamflow ratios of six index basins and statewide temperature shifts, along with precipitation change ratios for 12 climate change scenarios developed by Lawrence Berkeley National Laboratory, climate-perturbed 72 year historical monthly hydrological time series of rim inflows, reservoir evaporation rates, local surface water accretions, and groundwater inflows were generated for California's intertied water system. Various analyses of the perturbed hydrological time series have been done and the statistics show that the perturbed hydrology can be a reasonable hydrologic representation of the 12 climate scenarios. The perturbed hydrology will form a basis for water supply system planning and management studies using the CALVIN economic engineering optimization model. Without operation modeling, approximate changes in water availability are estimated for the 12 climate change scenarios. These changes are compared with estimated changes in urban and agricultural water use between now and 2100.

A.1 Introduction

This attachment discusses California's hydrology under projected climate changes. Monthly streamflow incremental ratios at six index basins, statewide temperature shifts, and precipitation changes were used to perturb CALVIN hydrology. Lawrence Berkeley National Laboratory (LBNL) developed these ratios and shifts (Miller et al., 2001). The CALVIN hydrology consists of 72 year (October 1921 through September 1993) monthly time series of rim inflows, reservoir evaporation rates, local accretions, and groundwater inflows. Excel VBA-based object-oriented software was developed to calculate the climate-perturbed CALVIN hydrology for different combinations of CALVIN regions, hydrological components, mapping methods, and climate scenarios.

This attachment begins with an overview of general climate change issues and California's historical climate and then introduces projected California climate scenarios developed by LBNL. In following sections, methods and results of perturbed rim inflows, reservoir evaporation rates, local surface accretions, groundwater inflows, total quantities, and water availabilities are presented, and the strengths and weakness of each part are discussed. At the end of the attachment, several tables are presented to show the spatially distributed results for each inflow and reservoir location.

A.1.1 General climate change issues

Research in several areas of geology indicates that climate has changed throughout the history of our planet (Dam, 1999). The latest 2001 Intergovernmental Panel on Climate Change (IPCC report reaffirms that climate is changing in ways that cannot be accounted for by natural variability and that “global warming” is occurring (IPCC, 2001). The major cause of warming is thought to be from human activity — primarily the use of fossil fuels — changing the composition of the atmosphere.

The IPCC reports that climate model projections with a transient 1% annual increase in greenhouse gas emissions show an increase in the global mean near-surface air temperature. The temperature increase ranges from 1.4°C to 5.8°C, with a 90% probability interval of 1.5°C to 4.5ºC by 2100 (Wigley and Raper, 2001). This projected change is larger than any climate change experienced in the last 10,000 years.

Climate change has several influences on hydrology. The main components of the hydrologic cycle are precipitation, evaporation, and transpiration. Changes in the climate parameters — solar radiation, wind, temperature, humidity, and cloudiness — will affect evaporation, transpiration, and the form of precipitation. Changes in evapotranspiration and precipitation will affect the amount, as well as the temporal and spatial distribution of soil moisture and surface runoff. As global and regional temperatures increase, there will be changes in rainfall patterns throughout the world, increases in evaporation rates, and changes in hydrologic variability (Dam, 1999). Modeling studies of the association between climate change and water resources have focused particularly on the relationships between streamflow, precipitation, and temperature (Risbey and Entekhabi, 1996).

Climate change might influence the hydrologic cycle at different temporal and spatial scales. The driving meteorological variables can be estimated from general circulation model (GCM) scales. Assessing climate change and its likely impacts on the hydrologic cycle is extremely complex. Several global and regional scale studies have been done (Lettenmaier and Gan, 1990; Nijssen et al., 2001). Likely changes during the 21st century include higher maximum and minimum temperatures, more intense precipitation events, increased summer drying, and increased risk of drought and flood.

A.1.2 California climate and historical climate change

A.1.2.1 California climate and hydrology

Water is scarce in California. The state has a nice Mediterranean climate, with cool wet winters and warm dry summers, but a water supply that is poorly distributed in both time and space. On average, half the annual precipitation occurs in the three months of December, January, and

February. Three-fourths occurs in the 5 month period from November through March. The only significant departures are in the dry southeastern desert areas, which have a summer monsoon peak as well as a winter season maximum.

In California the wetter regions contributing most of the runoff are in the north. Most demand for water is in the central and southern portions of the state. Three-fourths of the state's 71 million acre-feet (MAF) of average natural runoff originates north of Sacramento; about 80% of urban and agricultural water demand is south of Sacramento (Roos, 2001).

A.1.2.2 Historical climate

To understand how future climate change will affect water resources, it is important to understand historical climate.

The Sierra Nevada mountains are California's most important catchment area, providing two-thirds of the state's developed surface water supply. Until recently, the most severe and persistent drought of California's historical record occurred between 1928 and 1934, when runoff was below average (Department of Water Resources, 1994). However, Stine (1994) studied the tree stumps rooted at four present day sites in the Sierras (Mono Lake, Tenaya Lake, the West Walker River, and Osgood Swamp), which suggested that California's Sierra Nevadas experienced extremely severe drought conditions for more than two centuries before A.D. ~1112 and for more than 140 years before A.D. ~1350. During these periods, runoff from the Sierra Nevadas was significantly lower than during any of the persistent droughts in the region during the past 140 years. Stine suggested that the droughts might have been caused by reorientation of the midlatitude storm tracks, a general contraction of circumpolar vortices, a change in the position of the vortex waves, or all three. If this reorientation was caused by medieval warming, future warming from natural or anthropogenic sources warming may cause a recurrence of such extreme drought conditions.

Stine (1994) noted that the findings support the notion that the medieval climate anomaly was a global phenomenon and that the aberrant atmospheric circulation of medieval times seems to have brought to some regions of the world a far greater departure in precipitation than in temperature. California's medieval precipitation regime, if it occurred with today's burgeoning human population, would be highly disruptive environmentally and economically. This emphasizes the importance of considering changes in precipitation, rather than simply in temperature, when weighting the potential impacts of future global climate change.

Stine (1996) also examined the Sierra Nevada climate from 1650 through 1850. His main conclusions were:

- Growing-season temperatures reached their lowest level of the past millennium around 1600 and then remained low, by modern (1928-1988) standards, until around 1850.

- The period from 1713 to 1732 was, by modern standards, characterized by relatively wet conditions. It was preceded by a century dominated by low precipitation, and followed by 130 years (particularly the intervals from 1764 to 1794 and 1806 to 1861) of anomalous drought.

- The period from 1937 to 1986 has been the third-wettest half-century interval of the past 1,000 years.

To gain a long-term perspective on hydrologic drought, Meko et al. (2001) reconstructed Sacramento River annual flow back to A.D. 869 from tree rings. The results suggest that persistent high or low flows over several decades characterize some part of the long-term flow history. The reconstruction supported using the 1930s as a design period of extreme drought with duration of perhaps 6 to 10 years. Because Meko's reconstruction of Sacramento River system runoff does not match the severity of the Stine droughts, we are not sure how widespread they were.

A.1.3 California projected climate by LBNL

The spatially distributed California flow impacts of climate change presented in this attachment are based on streamflow estimates for six California basins that Miller et al. (2001) generated for 12 climate scenarios.

A.1.3.1 Climate scenarios and the hydrologic model

Because of the uncertainty inherent in projecting future climate, Miller et al. (2001) applied a range of potential future climatological temperature shifts (1.5ºC, 3.0ºC, and 5.0ºC) and precipitation changes (0%, 9%, 18%, and 30%) to the National Weather Service River Forecast System (NWSRFS) Sacramento Soil Moisture Accounting (SAC-SMA) Model and Anderson Snow Model to assess hydrologic sensitivities. Two GCM projections for three projected future periods (2010-2039, 2050-2079, and 2080-2099) were also used in this analysis; one projection is warmer and wetter (the Hadley Climate Centre's HadCM2 run 1) and one is cooler and drier (parallel climate model [PCM] run B06.06), relative to the GCM projections that were part of the IPCC's Third Assessment Report (McCarthy et al., 2001). The IPCC projections were statistically downscaled to a 10 km spatial resolution and a month-to-month temporal resolution, which more tightly focused the global climate change data onto California. Finally, the NWSRFS SAC-SMA model was used to estimate the impacts of these average monthly temperature and precipitation projections on six California watersheds. This hydrologic model system estimates how temperature and precipitation contribute to soil moisture, snowpack, snowmelt, and ultimately streamflow. The model system was specifically chosen because it is the operational model used by the NWS, meaning that it has considerable empirical validity and has received scrutiny over a significant period of time.

The 12 climate scenarios include:

1. 1.5ºC temperature increase and 0% precipitation increase (1.5 T 0% P)
2. 1.5ºC temperature increase and 9% precipitation increase (1.5 T 9% P)
3. 3.0ºC temperature increase and 0% precipitation increase (3.0 T 0% P)
4. 3.0ºC temperature increase and 18% precipitation increase (3.0 T 18% P)
5. 5.0ºC temperature increase and 0% precipitation increase (5.0 T 0% P)
6. 5.0ºC temperature increase and 30% precipitation increase (5.0 T 30% P)
7. HadCM2 2010-2039
8. HadCM2 2050-2079
9. HadCM2 2080-2099
10. PCM 2010-2039
11. PCM 2050-2079
12. PCM 2080-2099.

A.1.3.2 Geographic and hydrologic characteristics of the six index basins

Miller et al. (2001) chose six representative headwater basins (Smith River at Jed Smith State Park, Sacramento River at Delta, Feather River at Oroville Dam, American River at North Fork Dam, Merced River at Pohono Bridge, and Kings River at Pine Flat Dam) with natural flow for analysis in this study (Figure A.1). The six California basins stretch from the northernmost area to the east-central region of the state.

Table A.1 shows basin size, location, and percentage area of upper sub-basin, as well as the centroid of each upper and lower sub-basin. The gauge name, gauge latitude and longitude, and elevation of each corresponding CALVIN rim inflow location also are shown in Table A.1 for comparison purposes. Among the six index basins, the Smith is a very wet coastal basin that does not significantly accumulate seasonal snowpack. The Sacramento is a mountainous northern California basin with a small amount of seasonal snow accumulation. The Sacramento provides streamflow for the north and northwest drainage region into the Central Valley. The Feather and the Kings represent the northernmost and southernmost Sierra Nevada basins for this study, and the Kings and Merced are the highest elevation basins. The American is a fairly low-elevation Sierra Nevada basin, but frequently exceeds flood stage, resulting in substantial economic losses. This set of study basins provides fairly broad information for spatial estimates of the overall

Figure A.1. Location of the six index basins (Miller et al., 2001)

response of California's water supply (excluding the Colorado River) and will help indicate the potential range of hydrologic impacts. Figure A.2 shows the CALVIN model's 72 inflow and local accretion locations, 47 reservoir locations, and 28 groundwater basins' centroid in the five modeled regions.

A.1.4 Summary of LBNL results for index basins

For each climate change scenario, runoff was calculated for the six California index basins that extend from the coastal mountains and northern Sierra Nevada region to the southern Sierra Nevada region. For all scenarios, a larger proportion of the annual streamflow volume occurs earlier in the year because of fewer freezing days during the winter months. The amount and timing of changes depend on the characteristics of each basin, particularly the portion of drainage above the elevation of the freezing line. The hydrologic response varies for each scenario and the resulting solution set provides bounds to the range of likely changes in streamflow, snowmelt, snow water equivalent, and the change in the magnitude of annual high flow days. Table A.2 shows annual and seasonal changes compared to the historical streamflow of each basin for each climate change scenario.

Table A.1. Comparison of index basins and corresponding CALVIN rim inflow locations

Basin/inflow location		Smith	Sacramento	Feather	American	Merced	Kings
LBNL index basin (Miller et al., 2001)	Area	1706 km^2	1181 km^2	9989 km^2	950 km^2	891 km^2	4292 km^2
	Gage latitude	41º 47’ 30” N	40º 45’ 23” N	39º 32’ 00” N	38º 56’ 10” N	37º 49’ 55” N	36º 49’ 55” N
	Gage longitude	124º 04’30” W	122º 24’ 58” W	121º 31’ 00” W	121º 01’ 22” W	119º 19’ 25” W	119º 09’ 25” W
	Percent upper[a]	0	27	58	37	89	72
	Upper centroid[b]	N/A	1798	1768	1896	2591	2743
	Lower centroid[c]	722	1036	1280	960	1676	1067
CALVIN rim inflow location	Location	N/A	Shasta Lake	Oroville Lake	Folsom Lake	Lake McClure	Pine Flat Reservoir
	Gage latitude	N/A	40° 43’ 01’’ N	39º 32’ 00” N	38°42’00’’ N	37º 35’ 02” N	36º 49’ 51” N
	Gage longitude	N/A	122° 25’ 01’’W	121º 31’ 00” W	121° 10’ 01’’W	120º 16’ 01” W	119º 20’ 06” W
	Gage elevation	N/A	1075 ft	300 ft	466 ft	867 ft	557 ft

a. Area percentage of upper sub-basin.
b. Elevation of upper sub-basin centroid.
c. Elevation of lower sub-basin centroid.

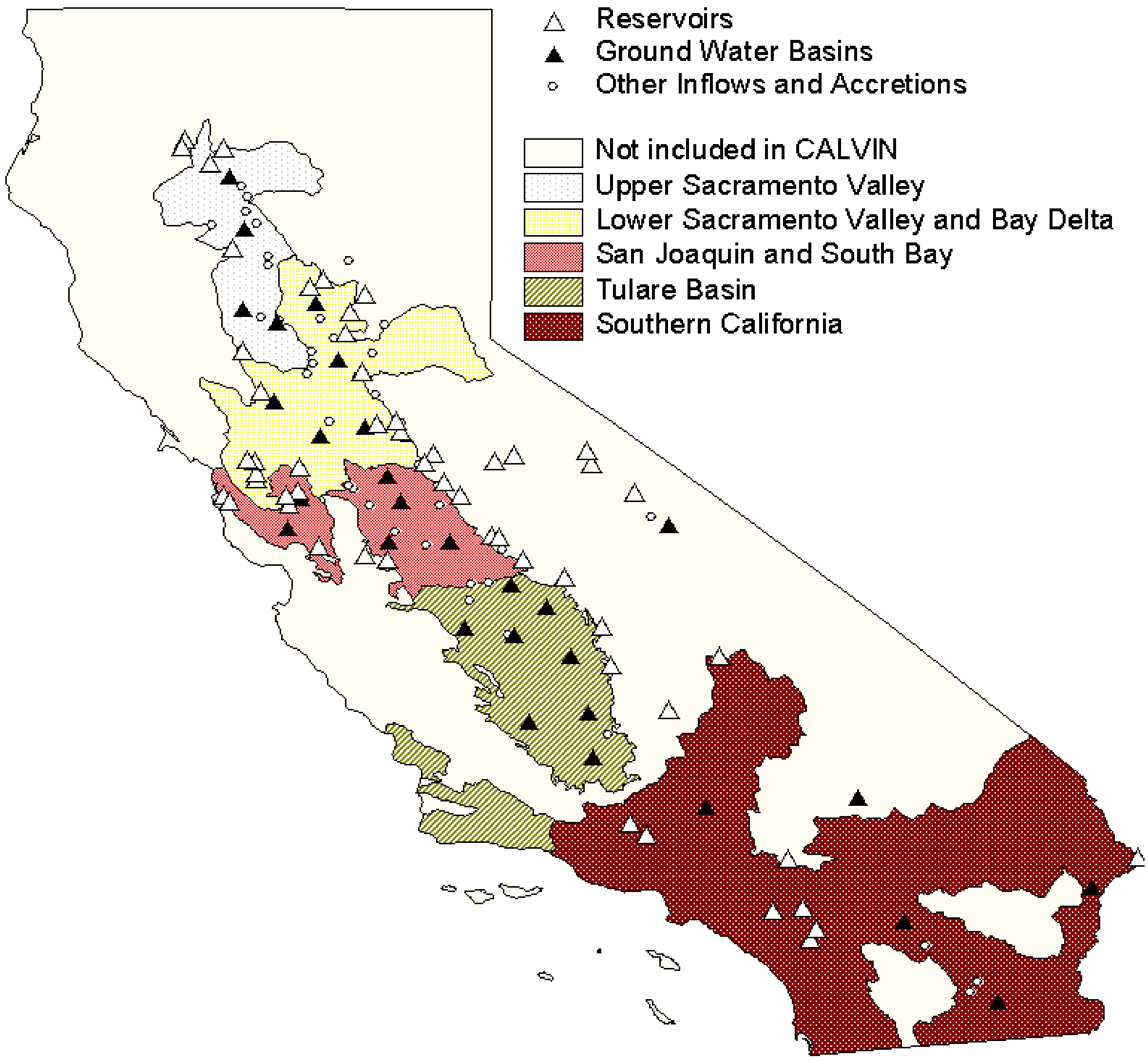

Figure A.2. CALVIN modeled demand regions, inflows, and reservoirs

Table A.2. Average percent changes of index basin runoff compared with historical data

	Smith			Sacramento			Feather			American			Merced			Kings		
Scenario	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	-6.9	-6.4	-9.2	-6.0	6.0	-24.7	-3.6	15.5	-30.8	-6.6	8.5	-29.5	-7.5	62.2	-21.1	-5.3	9.5	-10.9
2	3.5	4.7	-1.2	6.2	20.5	-16.2	9.9	31.7	-21.2	7.7	25.6	-19.6	6.8	88.1	-9.2	7.5	24.8	0.9
3	-7.0	-6.4	-9.3	-5.3	16.8	-39.7	-3.0	28.9	-48.2	-7.0	19.5	-47.4	-8.3	151.2	-39.6	-4.0	37.7	-19.9
4	13.8	15.6	6.4	19.4	48.8	-26.6	24.5	66.8	-35.8	22.0	57.7	-32.6	20.0	225.1	-20.2	22.0	75.6	1.6
5	-7.0	-6.5	-9.3	-5.0	22.7	-48.2	-3.8	33.9	-57.4	-8.2	23.9	-57.0	-9.9	262.4	-63.3	-2.2	90.2	-37.5
6	27.7	30.4	16.8	36.4	80.1	-31.8	42.1	102.0	-43.0	40.6	92.7	-38.8	37.3	443.3	-42.3	41.0	175.7	-10.4
7	12.4	13.7	7.0	19.5	36.6	-7.4	31.2	59.5	-9.0	34.3	55.3	2.2	35.1	127.3	17.0	39.2	59.5	31.5
8	17.4	23.1	-6.1	27.1	56.8	-19.2	43.3	88.1	-20.3	47.5	86.5	-12.0	47.1	227.7	11.7	51.3	101.2	32.3
9	35.4	43.8	1.0	49.3	96.9	-24.8	71.9	143.5	-29.8	76.1	141.1	-22.9	81.2	417.3	15.3	99.7	202.1	60.6
10	-14.9	-16.8	-6.9	-14.4	-15.3	-13.1	-12.7	-11.4	-14.5	-11.8	-12.0	-11.5	-7.3	11.0	-10.9	-9.9	-5.6	-11.5
11	-20.2	-21.3	-15.9	-18.8	-10.8	-31.4	-17.2	-3.1	-37.2	-22.1	-12.3	-36.9	-24.0	13.7	-31.4	-19.8	-8.4	-24.2
12	-25.5	-28.4	-13.6	-27.5	-18.9	-40.9	-30.5	-15.9	-51.1	-36.2	-26.8	-50.5	-38.9	26.4	-51.7	-32.5	-13.1	-39.9
Historical (MAF)	2.87	2.31	0.57	0.92	0.56	0.36	4.68	2.75	1.93	0.61	0.37	0.24	0.50	0.08	0.42	1.84	0.51	1.33

Source: Miller et al., 2001.

A.1.5 Other views of climate change for California

In many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to California's water system (Wilkinson, 2002). Several investigations of California's hydrologic response to climate change have focused on changes in streamflow volumes and timing. In general, these studies suggest that Sierra Nevada snowmelt-driven streamflows are likely to peak earlier in the season under global warming.

Lettenmaier and Gan (1990) studied the hydrological sensitivity of four medium-sized mountainous catchments in the Sacramento-San Joaquin River Basins to long-term global warming. The selected catchments were (1) McCloud River near McCloud (USGS 11-3675; 358 square miles); (2) Merced River at Happy Isles Bridge (USGS 2645; 187 square miles); (3) North Fork of the American River at North Fork Dam (USGS 11-4170; 342 square miles); and (4) Thomes Creek at Paskenta (USGS 11-3820; 203 square miles).

To simulate the hydrologic responses of these snowmelt-driven catchments, snowmelt and soil moisture accounting models from the NWSRFS were coupled. In all four catchments, the global warming pattern indexed to carbon dioxide (CO_2) doubling scenarios simulated by three GCMs produced a major seasonal shift in the snow accumulation pattern. The conclusions were that: (1) the general warming simulated by all the GCMs under CO_2 doubling would substantially decrease average snow accumulations in all studied catchments; (2) reduction in precipitation occurring as snow would increase winter runoff and decrease spring and summer runoff; and (3) increased precipitation occurring as rainfall in the winter months would increase winter soil moisture storage and would make more moisture available for evapotranspiration (ET) in the early spring. Increased temperatures would increase spring ET.

A.2 CALVIN Rim Inflows

The CALVIN model has 37 inflows into the Central Valley from the surrounding mountains, which are called rim inflows. Historically, these rim inflows average 28.2 MAF/yr, accounting for 72% of all inflows into CALVIN's California intertied water system. The basic idea of rim inflow perturbation is to map hydrologic regime changes of the six index basin streamflows to the 37 CALVIN basin rim inflows.

A.2.1 Mapping method

To map the appropriate incremental ratios to CALVIN rim inflows, several methods were tried and some lessons were learned. In addition, some satisfactory results were obtained. It proved almost impossible to find reasonable matches for all the CALVIN inflows with only one method.

The various statistical approaches to identify corresponding index basins for each CALVIN inflow include:

1. maximum annual flow correlation coefficient between CALVIN inflows and index basin flows

2. maximum monthly flow correlation coefficient between CALVIN inflows and index basin flows

3. multiple regression mapping by year

4. multiple regression mapping by month

5. wet and dry seasons (October to March and April to September) least sum of squared error (SSE) of monthly percentage distribution of annual flow

6. visual comparison (by runoff monthly distributions, gage**,** geographic locations, and hydrologic processes — snowmelt runoff or not).

Finally, methods (1), (5), and (6) were combined to establish a 37×2 mapping matrix to identify the most appropriate index basins for wet and dry seasons for each CALVIN rim inflow. With method (6), the monthly rim inflow incremental ratios of some index basins were shifted forward or backward by 1 month, representing snowmelt timing changes to obtain the best fit for CALVIN inflow locations on the east side of the Sierras.

For the maximum correlation coefficient criterion, annual rim inflow correlation coefficients were calculated between each index basin and each CALVIN rim inflow for the water years from 1963 to 1993. Miller et al. (2001) simulated the six index basin flow series. The rim inflow series are taken from CALVIN hydrology. For each CALVIN rim inflow, the index basin with the maximum annual rim inflow correlation coefficient was chosen as the best mapping basin. For instance, with Method (1) , the index basin i (i = 1, 2, …, 6) is identified by

$$I = \max_{i} \{ r_{ij} \} \tag{A.1}$$

where i (i = 1, 2, …, m) represents index basin; j (j = 1, 2, …, n) represents CALVIN inflow; and r_{ij} represents the annual flow correlation coefficient between index basin i and CALVIN inflow j.

Method (5) identifies the index basins for the wet season and the dry season, respectively, for each CALVIN inflow, based on the index basin that has the least SSE of the monthly percentage distribution of annual streamflow (based on water year) with the CALVIN inflow monthly percentage distribution. To partition a water year into a wet season and a dry season facilitates finding the best fit for snowmelt- versus rainfall-driven runoff regimes. For instance, the most appropriate index basin for CALVIN inflow j in the wet season can be identified by:

$$I = \min_{i} \sum_{k \in Wet} \left(P_{ik} - P_{jk}\right)^2 \tag{A.2}$$

where i (i = 1, 2, . . . , m) represents index basins, j (j = 1, 2, . . . , n) represents CALVIN rim inflow locations, and P_{ik} represents the k^{th} month percentage of annual streamflow of index basin i.

Method (6) compares the monthly percentage distribution of annual streamflow of index basins with CALVIN inflows in the wet season and the dry season and identifies a 1-month lag or shift in the distribution for an index basin in a few cases when that produces the best matching pattern. Figure A.3 compares the monthly percentage distribution of annual streamflow of the six index basins with six CALVIN inflows: Cottonwood Creek, LV-Haiwee, Upper Owens, French Dry Creek, San Joaquin River, and Merced River. For instance, it was found through comparison that the monthly distribution of the Smith River is most similar to that of Cottonwood Creek, and LV-Haiwee fits with Kings River very well after the LV-Haiwee is shifted to the left by 1-month (LV-Haiwee has already been shifted in Figure A.3).

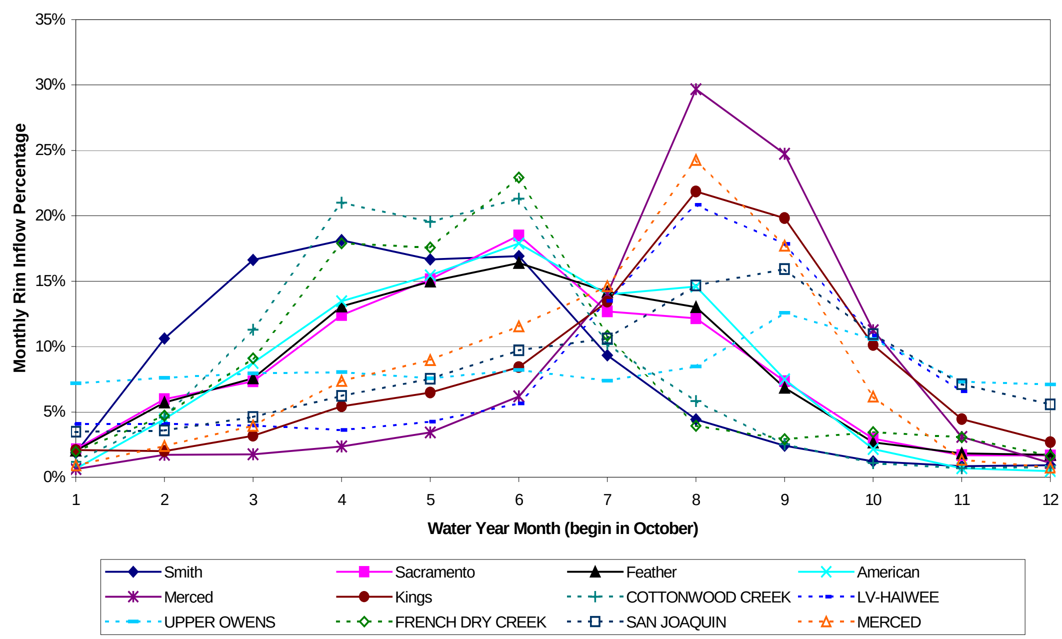

Figure A.3. Visual comparison of rim inflow percentage

A.2.2 Rim inflow calibration

For each scenario, the relative flow changes of each perturbed CALVIN rim inflow should be close to the relative changes of its index basins (Table A.2). Numerous calibration and re-calculation iterations were carried out to find the “best” mapping matrix. To calibrate perturbed CALVIN rim inflows against those at index basins, first Method 1 was employed and problematic mappings were identified by comparing the changes against those at index basins.

Second, new index basins for these problematic CALVIN inflows were identified with Method 5, and again, the remaining problematic mappings were determined. Finally, the remaining problematic CALVIN rim inflows were dealt with by Method 6, usually involving several trial and error processes. For the 37 CALVIN rim inflows, 18 are mapped with Method 5, 12 with Method 6, and 7 with Method 1. Numerous trial and error processes showed that different CALVIN rim inflows have different hydrologic characteristics and need different methods to relate them to the index basins. This combination of the three methods is the “best” approach that we explored for mapping climate-induced flow changes of the six index basins to the 37 CALVIN rim inflows. Table A.3 shows index basins for each CALVIN rim inflow.

A.2.2.1 Results of perturbed rim inflows

Table A.4 shows the total quantities and changes for the 37 CALVIN rim inflow basins. A wide range of projected changes in rim inflows is given. For instance, the total annual rim inflows could be 76.5% more than historical under a warm wet GCM climate scenario (HadCM2 2080-2099), and 25.5% less under a cool dry climate scenario (PCM 2080-2099). Except for the three PCM scenarios, there is an increase in inflow in the wet season. In all but the HadCM2 scenarios, there is a decrease in inflow in the dry season. Even in the three wet and warm HadCM2 scenarios, inflow increases in winter are much higher than in summer, resulting in an overall shift in annual runoff from the dry to the wet season seen in all scenarios except PCM 2010-2039.

The monthly mean overall rim inflows for the 12 climate scenarios and historical data are plotted in Figure A.4. The results show that these climate changes would significantly shift the peak runoff of catchments where the annual hydrograph is currently dominated by spring snowmelt. Much more runoff would occur in winter and less in spring and summer.

Table A.5 (a-c) shows regional analyses for rim inflows in five CALVIN regions (Figure A.2). Northern regions 1 and 2 account for 68% of annual rim inflows; southern regions 4 and 5 account for only a small portion of the annual rim inflows. With the warm and wet HadCM2 2080-2099 scenario, rim inflows in the south increase with higher percentages than in the north. With the cool and dry PCM 2080-2099 scenario, rim inflows decrease in all regions.

Table A.3. Wet and dry season index basins for each CALVIN rim inflow

CALVIN rim inflow	Wet season index basin	Dry season index basin	CALVIN rim inflow	Wet season index basin	Dry season index basin
1. Trinity River	Sacramento	Sacramento	20. Greenhorn Creek and Bear River	American	American
2. Clear Creek	Smith	Smith	21. Kelly Ridge	Smith	Smith
3. Sacramento River	Sacramento	Sacramento	22. Stanislaus River	Feather	Kings
4. Stony Creek	Smith	Smith	23. San Joaquin River	Feather	Kings
5. Cottonwood Creek	Smith	Smith	24. Merced River	Feather	Kings
6. Lewiston Lake Inflow	Feather	American	25. Fresno River	Smith	Smith
7. Middle and South Forks Yuba River	American	American	26. Chowchilla River	Smith	Smith
8. Feather River	Feather	Sacramento	27. Clocal inflow to New Don Pedro	Sacramento	American
9. North and Middle Forks American River	American	American	28. Tuolumne River	Merced	Merced
10. South Fork American River	Feather	Feather	29. Cherry and Elnor	Kings	Merced
11. Cache Creek	Smith	Smith	30. Santa Clara Valley Local	Smith	Smith
12. Putah Creek	Smith	Smith	31. Kern River	Kings	Kings
13. North Fork Yuba River	Feather	Feather	32. Kaweah River	Kings	Merced
14. Calaveras River	Smith	Smith	33. Tule River	Feather	Feather
15. Mokelumne River	Feather	Kings	34. Kings River	Kings	Kings
16. Cosumnes River	American	Feather	35. Lower Owens Valley — Haiwee	Kings	Kings
17. Deer Creek	Smith	Smith	36. Mono Basin	Merced	Kings
18. Dry Creek	Smith	Smith	37. Upper Owens	Kings	Sacramento
19. French Dry Creek	Smith	Smith			

Table A.4. Overall rim inflow quantities and changes

	Annual		October-March		April-September	
Climate scenario	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**
1. 1.5 T 0% P	28.6	1.1	16.4	15.6	12.2	-13.4
2. 1.5 T 9% P	32.4	14.6	18.7	31.7	13.7	-2.7
3. 3.0 T 0% P	28.5	0.9	18.2	28.0	10.3	-26.5
4. 3.0 T 18% P	36.2	28.1	23.3	64.4	12.8	-8.7
5. 5.0 T 0% P	27.9	-1.1	19.5	37.1	8.5	-39.7
6. 5.0 T 30% P	40.6	43.7	28.9	103.8	11.7	-17.0
7. HadCM2 2010-2039	38.5	36.4	22.0	54.9	16.5	17.6
8. HadCM2 2050-2079	41.3	46.4	25.8	82.0	15.5	10.4
9. HadCM2 2080-2099	49.8	76.5	33.3	134.3	16.6	18.1
10. PCM 2010-2039	26.5	-6.2	13.2	-6.7	13.2	-5.7
11. PCM 2050-2079	24.4	-13.6	13.7	-3.8	10.7	-23.5
12. PCM 2080-2099	21.1	-25.5	12.2	-14.2	8.9	-36.9
Historical	28.2	0.0	14.2	0.0	14.0	0.0

In the wet season, rim inflows increase in all regions in all scenarios except the PCM scenarios. Rim inflows in the south increase at higher percentages than in the north for all except the PCM scenarios. In the dry season, rim inflows decrease for all regions for all scenarios except HadCM2 2080-2099, where only regions 1 and 2 experience inflow reduction. For most cases, rim inflows in the north decrease more seriously than in the south during dry season. These regional conclusions should be tempered by understanding that mapping inflows to index basins tended to be poorer further south, where there were fewer index basins.

Considering these results, Figure A.4 shows that the monthly average of 72 year perturbed rim inflows for the 12 climate change scenarios gives an important and reasonable range of hydrological responses to climate change in California. As statistical interpolations and extrapolations of the changes projected for the six index basins, the perturbed CALVIN rim inflows present a reasonable set of projections under different climate change scenarios. However, for a few CALVIN rim inflows, especially those in the southern parts of the state, the annual and seasonal mean changes are not very close to those of index basins under the same climate change scenarios. For instance, San Joaquin River has a -10.3% annual inflow reduction under the 5.0 T 0% P uniform incremental scenario, while the corresponding changes of its two index basins, the Feather River and the Kings River, are 3.1% and 4.8%, respectively. The San Joaquin River annual rim inflow is 1.681 MAF, accounting for 6% of the total amount of annual rim inflows. From Figure A.3, it is apparent no index basin exists with a monthly distribution pattern similar to that of the San Joaquin. The result for the San Joaquin River, then, is not very

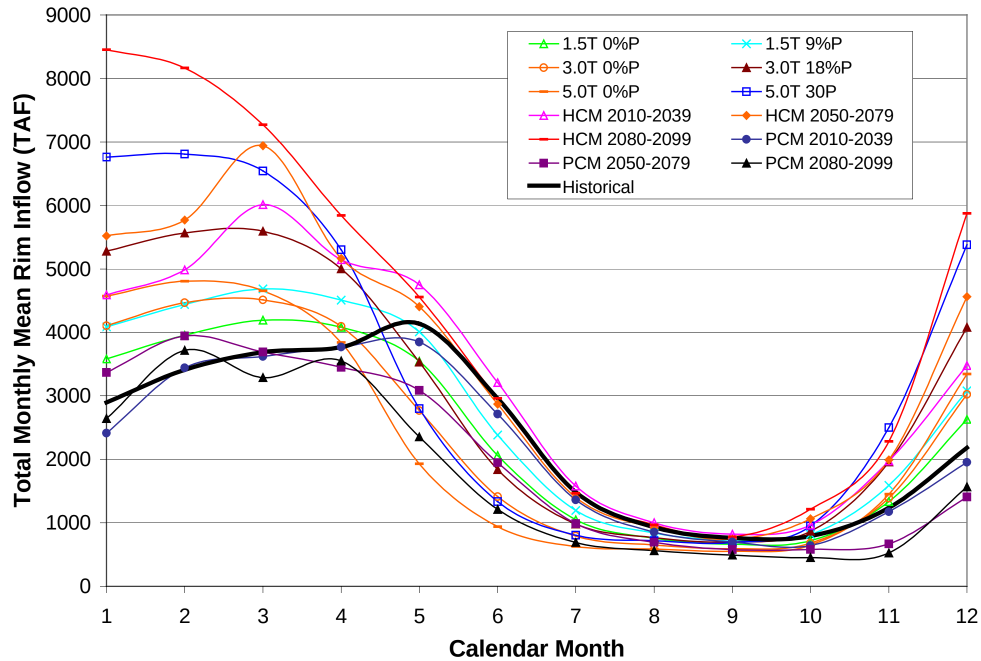

Figure A.4a. Monthly mean rim inflows (72-year) for the 12 climate scenarios and historical data

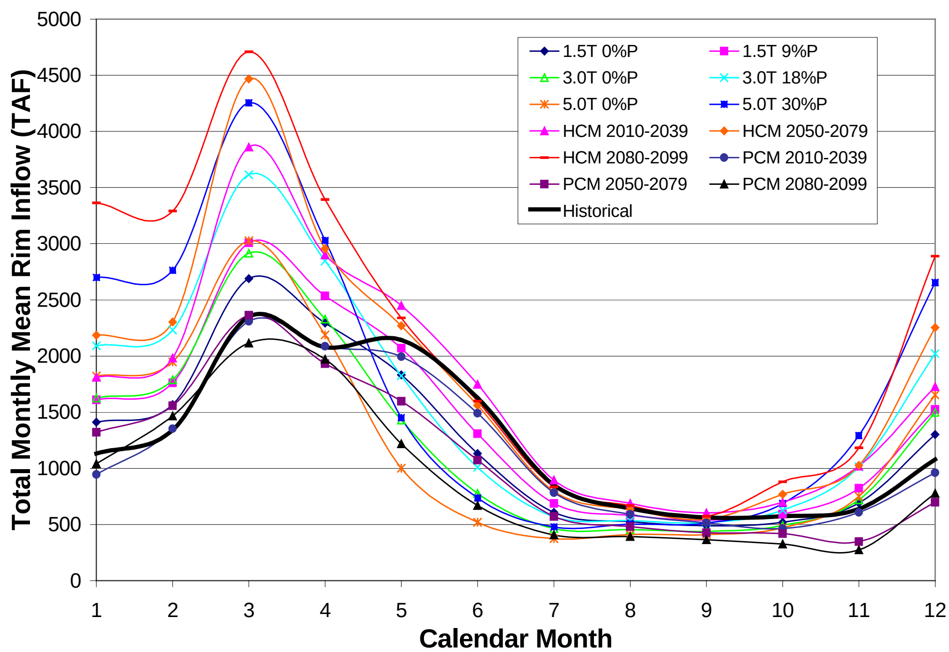

Figure A.4b. Monthly mean rim inflows (14 drought years) for the 12 climate scenarios and historical data

Table A.5a. Annual rim inflow (%) regional analysis

Region	Historical annual (TAF)[a]	Climate change scenario				
		3.0 T 0% P	5.0 T 0% P	5.0 T 30% P	HadCM2 2080-2099	PCM 2080-2099
1	8002	0.6	1.1	43.8	56.3	-22.1
2	11120	1.3	-0.3	46.1	75.1	-25.5
3	5741	1.3	-5.5	38.9	91.4	-27.6
4	2826	0.0	-1.3	43.8	104.9	-29.3
5	555	-2.8	-0.2	45.4	96.3	-31.5
Statewide	28244	0.9	-1.1	43.7	76.5	-25.5

a. Thousand acre-feet.

Table A.5b. Wet season rim inflow (%) regional analysis

Region	Historical October-March (TAF)	Climate change scenario				
		3.0 T 0% P	5.0 T 0% P	5.0 T 30% P	HadCM2 2080-2099	PCM 2080-2099
1	4872	20.3	26.0	84.0	101.9	-15.4
2	6323	28.1	32.3	99.4	139.9	-15.5
3	2097	38.3	52.8	127.7	158.3	-9.5
4	751	46.8	98.0	189.7	217.3	-7.5
5	156	35.6	76.7	168.4	195.4	-18.0
Statewide	14199	28.0	37.1	103.8	134.3	-14.2

Table A.5c. Dry season rim inflow (%) regional analysis

Region	Historical April-September (TAF)	Climate change scenario				
		3.0 T 0% P	5.0 T 0% P	5.0 T 30% P	HadCM2 2080-2099	PCM 2080-2099
1	3130	-30.1	-37.7	-18.8	-14.7	-32.7
2	4797	-34.1	-43.2	-24.2	-10.3	-38.7
3	3643	-20.0	-39.1	-12.2	52.8	-38.0
4	2076	-17.0	-37.2	-8.9	64.2	-37.1
5	399	-17.8	-30.2	-2.5	57.6	-36.7
Statewide	14045	-26.5	-39.7	-17.0	18.1	-36.9

good. The same problem occurs with the Upper Owens located on the east side of the southern Sierras. It has an annual inflow of 0.143 MAF, accounting for only 0.5% of the annual total rim inflows. Flow quantities of these problematic rim inflow locations account for a small portion (less than 15%) of the total. However, they indicate that simulations of more index basins south of the delta, along the coast and in the Central Valley floor would be useful.

Flow quantities and percentage changes for all 37 rim inflows appear in Table A at the end of this attachment.

A.3 Reservoir Evaporation

The CALVIN model has 47 surface reservoirs for which evaporation is calculated. Historically, over the 72 year hydrology history used in CALVIN, 1.6 MAF/yr of water is lost from these reservoirs as net evaporation under current reservoir operations, which represents about 4% of all inflows. Changes in evaporation rate and in total evaporation, assuming the same operations, for each reservoir were estimated for each climate scenario.

A.3.1 Method description

The net evaporation rate at reservoir *i* is

$$NetE_i = E_i - P_i \tag{A.3}$$

where E_i is monthly evaporation rate and P_i is monthly precipitation rate. A two-variable linear regression equation can be employed to represent the historical empirical relationship between monthly average net evaporation rate in feet and monthly average air temperature and precipitation at each surface reservoir.

$$NetE_i = a_i T + b_i P + c_i \tag{A.4}$$

where T is monthly mean air temperature in degrees F, P is the monthly mean precipitation in feet, and a_i and b_i are regression coefficients. The CALVIN monthly average net evaporation rate (in feet) at each reservoir for the period from 1961 to 1990 was regressed against the NWS average monthly air temperature and precipitation data for the same period at the nearest weather station to each CALVIN reservoir (NWS, January 2002). At nearly all reservoirs, the regression analysis of the 12 months of average conditions produced very good fits.

The reservoir net evaporation rate increase for scenario *j* is obtained from the following empirical equation:

$$\Delta NetE_{ijm} = a_i \cdot \Delta T_{jm} + b_i \cdot \left(1 + \Delta P_{jm}\right)\overline{P_{im}} \qquad \text{(A.5)}$$

where $\Delta NetE_{ijm}$ is the average incremental net evaporation rate (feet) in month *m*, under climate scenario *j*, at reservoir *i*; ΔT_{jm} is the average temperature increase (ºF) in month *m* under climate scenario *j*; ΔP_{jm} is the average precipitation increase ratio under climate scenario *j* for month *m*; $\overline{P_{im}}$ is the historical m^{th} month average precipitation in feet at reservoir *i*; and a_i and b_i are coefficients the same as in the above regression equation. In the incremental climate scenarios (1 to 6), the temperature and precipitation shift is uniform in each month. In contrast, the GCM scenarios have average temperature and precipitation shifts that vary by month.

The monthly incremental net evaporation rate at each reservoir is then added to the historical monthly net evaporation rate time series for that reservoir. Next, the monthly net evaporation quantity, based on current storage operations, is obtained from the perturbed net evaporation rate using simulated historical reservoir monthly surface area.

$$NetEQ_{ijym} = NetE_{ijm} \times A_{iym} \qquad \text{(A.6)}$$

where $NetEQ_{ijym}$ is net evaporation quantity (net evaporation for short) at reservoir *i*, under scenario *j*, in the m^{th} month of the y^{th} year; and A_{iym} is the surface area of the i^{th} reservoir in the m^{th} month of the y^{th} year.

A.3.2 Results of net evaporation

Results show net evaporation increases between 3.6% and 41.3%. Most of the regression equations have a high significance level, with net evaporation rates being more sensitive to temperature than precipitation.

The perturbed CALVIN total reservoir evaporation can provide a reasonable estimate for changes in net evaporation losses under different climate scenario assumptions. However, there are some limitations to temperature- and precipitation-driven net evaporation change formulation, because evaporation changes tend to be physically driven by solar radiation changes (for which there is currently no accurate climate scenario information), rather than by ambient air temperature changes. Spatially, solar radiation is a function of cloud cover, which is a weak point of GCMs. Temperature changes are used as a surrogate and easy-to-obtain factor in this study.

Table A.6 shows average annual and seasonal surface reservoir evaporation quantities and changes over the 72 year hydrologic time series. The data indicate that reservoir evaporation increases for all 12 climate scenarios as a result of increased temperature. Relative increases are greater in the wet season, but absolute volume increases tend to greater in the dry season. For all GCM scenarios, evaporation will increase more over time.

Table A.6. Surface reservoir evaporation quantities and changes

	Annual		October-March		April-September	
Climate scenario	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**
1. 1.5 T 0% P	1.83	12.4	0.46	27.0	1.36	8.1
2. 1.5 T 9% P	1.81	11.6	0.45	24.3	1.36	7.9
3. 3.0 T 0% P	2.03	24.8	0.56	54.0	1.46	16.3
4. 3.0 T 18% P	2.00	23.2	0.54	48.5	1.46	15.8
5. 5.0 T 0% P	2.30	41.3	0.70	90.0	1.60	27.1
6. 5.0 T 30% P	2.25	38.6	0.66	80.9	1.59	26.3
7. HadCM2 2010-2039	1.77	9.0	0.43	16.8	1.34	6.7
8. HadCM2 2050-2079	1.90	16.9	0.49	33.3	1.41	12.1
9. HadCM2 2080-2099	1.98	21.7	0.52	40.7	1.46	16.2
10. PCM 2010-2039	1.68	3.6	0.40	8.0	1.29	2.3
11. PCM 2050-2079	1.84	13.5	0.48	30.8	1.37	8.5
12. PCM 2080-2099	1.98	21.6	0.55	49.9	1.43	13.4
Historical	1.62	0.0	0.37	0.0	1.26	0.0

Table B at the end of this attachment summarizes evaporation results for each of the 47 CALVIN surface reservoirs.

A.4 Groundwater and Local Surface Accretions

The CALVIN model has 28 groundwater inflows and 35 local surface water accretions. For the seven groundwater basins located outside the Central Valley, there are not enough data to model the relationship between precipitation and deep percolation recharge from rainfall. (For more details on CALVIN hydrology, see the technical appendices of Jenkins et al., 2001.) Therefore, only the 21 groundwater basins and 28 local surface accretions in the Central Valley have been perturbed for climate change. These 21 groundwater basins and 28 local surface accretions account for 6.8 and 4.4 MAF/yr, respectively, of total inflows into California's intertied water system, representing about 17% and 11%, respectively, of all inflows. Only a portion of the 6.8 MAF/yr of natural groundwater inflow is attributable to direct deep percolation of rainfall.

To estimate climate change effects on groundwater inflows and local surface water accretions, we partition precipitation changes into local runoff and deep percolation portions for each groundwater basin. These changes are then added to appropriate historical local accretion and groundwater inflow time series. We do not consider the unsaturated layer water balance or any changes in stream-aquifer exchanges from the CALVIN base case condition.

A.4.1 Estimating deep percolation changes

A cubic regression equation is employed to represent the nonlinear relationship between monthly deep percolation (in TAF) and precipitation (in TAF) for each groundwater basin from Central Valley Ground and Surface Water Model (CVGSM) simulated data over the 1922-1990 period (USBR, 1997) as shown below. It is assumed that no constant term is needed in the equation because deep percolation cannot happen without precipitation.

$$DP_i = a_i P_i^3 + b_i P_i^2 + c_i P_i \tag{A.7}$$

where DP_i is deep percolation at groundwater basin i in a month; P_i is monthly precipitation over groundwater basin i; and a_i, b_i, and c_i are regression coefficients. This relationship is demonstrated in Figure A.5 for groundwater basin 11.

The increased deep percolation can be represented with the differential form of the previous equation.

$$\Delta DP_i = \left(3a_i P_i^2 + 2b_i P_i + c_i\right) \times \left(\Delta P_i \times P_i\right) \tag{A.8}$$

where ΔP_i is average precipitation change ratio for the climate change scenarios.

Cubic regression equation was chosen because this form fits the empirical data for most groundwater basins very well. In addition, for most cases there is a peak plateau on the curve that can represent infiltration capacity.

For the six uniform incremental scenarios, the specified statewide annual average precipitation change was applied in each month. For the six GCM scenarios, temporally (monthly) and spatially distributed average precipitation change ratios were available for all 28 of the groundwater basins, based on the 1963-1993 climate simulation period. Table A.7 shows the average monthly precipitation change percentage for the 28 groundwater basins under the six GCM scenarios. Table A.8 shows the parameters and multiple correlation coefficients for the deep percolation regression equation for each of the 21 Central Valley groundwater basins. The high correlation coefficients indicate reasonable relationships between precipitation and deep percolation. The seven other basins were not modeled because no data are available to estimate the deep percolation equations. These groundwater basins are outside the Central Valley.

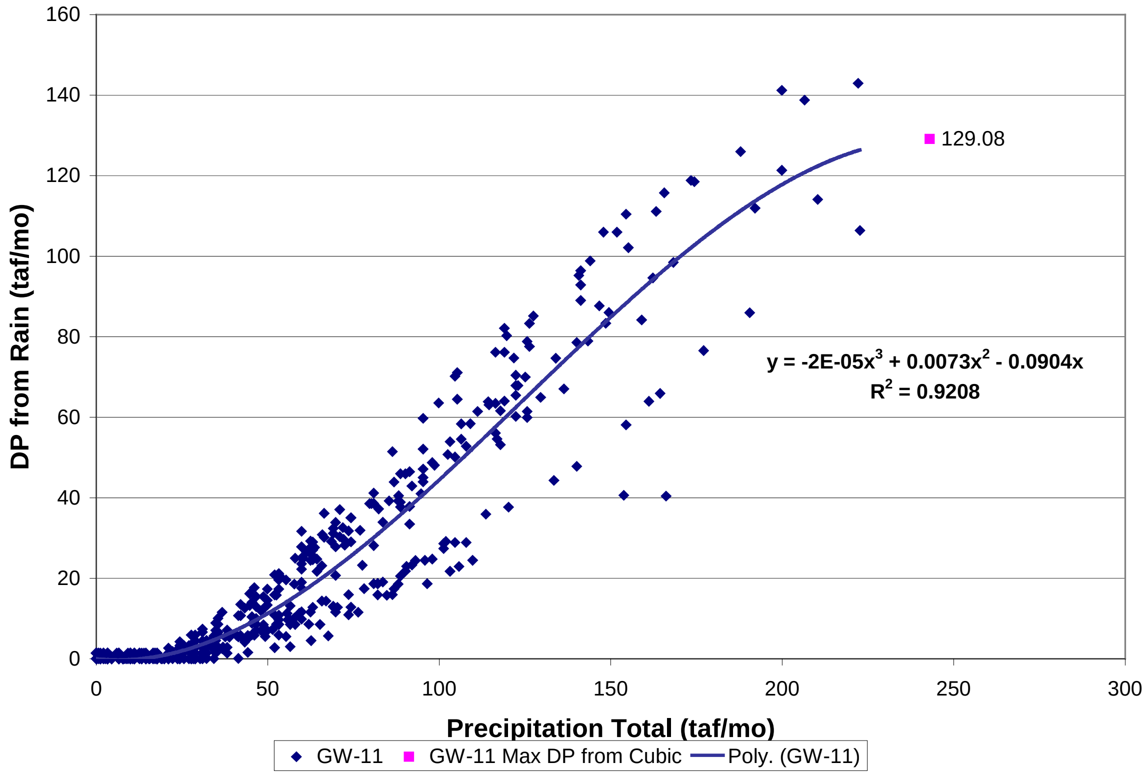

Figure A.5. Cubic regression curve for deep percolation in groundwater basin 11

Table A.7. Average percent monthly precipitation change ratios for GCM scenarios

Climate scenario	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
7. HadCM2 2010-2039	26	27	24	23	20	2	1	4	6	15	11	-5
8. HadCM2 2050-2079	33	34	34	30	32	17	18	24	22	29	37	25
9. HadCM2 2080-2099	62	62	57	55	59	49	40	43	38	45	56	64
10. PCM 2010-2039	-16	3	-25	-1	24	5	18	-16	-13	4	14	-18
11. PCM 2050-2079	-12	-13	-15	-14	-12	-17	-22	-22	-20	-19	-32	-27
12. PCM 2080-2099	-26	-27	-28	-27	-29	-30	-30	-31	-27	-21	-30	-16

Table A.8. Parameters of deep percolation equation for each groundwater basin

Ground-water basin	a	b	c	Multiple correlation coefficient	Ground-water basin	a	b	c	Multiple correlation coefficient
1	-2.89E-06	0.00140	0.03792	0.89	12	-5.6E-06	0.00126	0.05344	0.90
2	-1.753E-06	0.00150	-0.02612	0.92	13	-7.8E-07	0.00048	0.05044	0.86
3	-2.27E-06	0.00148	-0.05748	0.91	14	-3.9E-06	0.00385	-0.06876	0.96
4	-2.986E-06	0.00113	0.00558	0.93	15	-8.7E-07	0.00071	0.00933	0.89
5	-8.47E-07	0.00090	0.00624	0.93	16	-2.2E-06	0.00058	0.04886	0.89
6	-6.285E-07	0.00046	0.03964	0.89	17	-1.2E-07	0.00009	0.04782	0.86
7	-1.874E-07	0.00060	0.04097	0.86	18	-3.5E-07	0.00057	0.02269	0.92
8	-1.017E-07	0.00009	0.03983	0.86	19	-3.4E-06	0.00228	-0.02920	0.93
9	-1.427E-06	0.00116	-0.00505	0.88	20	-6.8E-06	0.00225	0.03627	0.89
10	-2.388E-06	0.00110	0.01743	0.89	21	-4.4E-06	0.00254	-0.01272	0.91
11	-1.952E-05	0.00730	-0.09043	0.96					

A.4.2 Groundwater inflow

Natural groundwater inflows or recharge (excluding recharge from operational deliveries to agricultural and urban demand areas), in the Central Valley from CVGSM can be represented as

$$I_i = DP_i + SA_i + BF_i + SS_i + LS_i + AR_i \qquad \text{(A.9)}$$

where:

DP_i = percolation of rain in basin *i*
SA_i = gain from streams in basin *i*
BF_i = gain from boundary flows (from outside the CVGSM modeled area) in basin *i*
SS_i = gain in basin i from subsurface flows across basin boundaries
LS_i = seepage from lake beds and bedrock in basin *i*
AR_i = seepage from canals and artificial recharge in basin *i*.

If we assume that other components of groundwater inflow are unchanged (a simplifying assumption), the change in groundwater inflow is equivalent to the change in deep percolation from changes in rainfall over the basin; that is,

$$I_{i,perturbed} = I_i + \Delta DP_i \qquad \text{(A.10)}$$

where $I_{i,perturbed}$ is perturbed groundwater inflows in basin *i*.

A.4.3 Local surface water accretion

Local surface water accretion can be represented as

$$LA_i = R_i + AG_i \qquad (AG_i = -SA_i) \tag{A.11}$$

where LA_i is net local surface water accretion, R_i is direct runoff, and AG_i is gain from aquifer. Increased local accretion over a groundwater basin, then, equals increased precipitation minus increased deep percolation, assuming a negligible change in evaporation from changed precipitation, which is probably not a major problem in most wet months. As a result, the perturbed local surface water accretion equals

$$LA_{i,perturbed} = LA_i + (\Delta P_i \times P_i - \Delta DP_i) \tag{A.12}$$

To connect groundwater inflow with local accretion, each groundwater basin is associated with a local accretion depletion area that coincides with the groundwater basin.

A.4.4 Results of groundwater inflows and local surface water accretions

Tables A.9 and A.10 show the annual and seasonal changes of groundwater inflows and local surface water accretions. In most cases, local surface water accretions and groundwater flows in the wet season greatly exceed those in the dry season. For all three future GCM periods, local surface water accretions and groundwater inflows increase with HadCM2 scenarios and decrease with PCM scenarios. Over time, local surface water accretions and groundwater inflows increase with HadCM2 scenarios, but decrease with PCM scenarios.

Results show that local surface water accretions are more sensitive to precipitation changes than groundwater inflows. This is mainly because the infiltration capacity effect in the regression analysis sets a limit for deep percolation, and therefore, most increased precipitation contributes to direct local runoff. Also, deep percolation of rainfall accounts for about 1.7 MAF/yr of the total 6.8 MAF/yr of average groundwater inflow in the Central Valley. Under the historical climate, this volume represents only about 12% of precipitation falling over groundwater basins in the Central Valley.

Table C at the end of this attachment summarize inflows and changes for each groundwater basin in the CALVIN model.

Table A.9. Groundwater inflow quantities and changes

	Annual		October-March		April-September	
Climate scenario	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)
1. 1.5 T 0% P	6.78	0.0	3.60	0.0	3.18	0.0
2. 1.5 T 9% P	7.01	3.4	3.80	5.5	3.21	1.0
3. 3.0 T 0% P	6.78	0.0	3.60	0.0	3.18	0.0
4. 3.0 T 18% P	7.24	6.8	4.00	11.1	3.24	1.9
5. 5.0 T 0% P	6.78	0.0	3.60	0.0	3.18	0.0
6. 5.0 T 30% P	7.55	11.3	4.27	18.5	3.28	3.2
7. HadCM2 2010-2039	7.51	10.7	4.17	15.8	3.33	5.0
8. HadCM2 2050-2079	7.68	13.3	4.42	22.7	3.26	2.5
9. HadCM2 2080-2099	8.37	23.5	5.08	41.1	3.29	3.5
10. PCM 2010-2039	6.61	-2.5	3.42	-5.0	3.19	0.3
11. PCM 2050-2079	6.44	-5.0	3.33	-7.6	3.11	-2.0
12. PCM 2080-2099	6.21	-8.5	3.08	-14.5	3.12	-1.7
Historical	6.78	0.0	3.60	0.0	3.18	0.0

Table A.10. Local surface water accretion quantities and changes

	Annual		October-March		April-September	
Climate scenario	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)	Quantity (MAF)	Change (%)
1. 1.5 T 0% P	4.42	0.0	3.54	0.0	0.88	0.0
2. 1.5 T 9% P	5.45	23.3	4.39	23.9	1.06	21.1
3. 3.0 T 0% P	4.42	0.0	3.54	0.0	0.88	0.0
4. 3.0 T 18% P	6.48	46.6	5.23	47.7	1.25	42.1
5. 5.0 T 0% P	4.42	0.0	3.54	0.0	0.88	0.0
6. 5.0 T 30% P	7.85	77.7	6.36	79.5	1.49	70.2
7. HadCM2 2010-2039	7.94	79.7	6.04	70.4	1.91	117.4
8. HadCM2 2050-2079	8.55	93.4	7.04	98.7	1.51	72.0
9. HadCM2 2080-2099	11.41	158.1	9.72	174.3	1.69	92.8
10. PCM 2010-2039	4.26	-3.5	3.23	-8.8	1.03	18.0
11. PCM 2050-2079	3.89	-12.0	3.08	-12.9	0.81	-8.2
12. PCM 2080-2099	3.17	-28.2	2.36	-33.2	0.81	-7.8
Historical	4.42	0.0	3.54	0.0	0.88	0.0

A.5 Total Water Quantity and Changes

Total water quantity available in a region is the sum of rim inflows, local net surface water accretions, and groundwater inflows, minus evaporation losses. Because rim inflows account for a large portion of overall water quantity in California, the changes in total water quantity are similar to those of rim inflows. However, groundwater and local accretion contribute significantly to overall water quantity, which make the overall changes slightly different from rim inflow changes. These differences are discussed in the next section.

In general, statewide results (see Tables A.11 and A.12) show that these climate changes would result in significant shifts in the peak season of water availability. Snowmelt comes much earlier than it has historically. Relatively more of the annual runoff would occur in the wet season and less in the dry season; wet seasons will become wetter and dry seasons will become drier. The three wet and warm HadCM2 scenarios indicate that future decades will experience much more water, and water availability will increase over time. The dry and cool PCM scenarios indicate that less water will be available and that conditions will worsen as time goes on. For drought years, overall water quantities show significant decreases for all scenarios except HadCM2 2080-2099. Compared with historical averages, drought years (1928-1934, 1976-1977, and 1987-1992) are expected to experience serious water decreases, although HadCM2 2080-2099 results show only moderate reductions.

Table A.11. Overall water quantities and changes

	Annual		October-March		April-September	
Climate scenario	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**	**Quantity (MAF)**	**Change (%)**
1. 1.5 T 0% P	37.9	0.3	23.1	10.1	14.9	-11.8
2. 1.5 T 9% P	43.0	13.7	26.4	26.0	16.6	-1.5
3. 3.0 T 0% P	37.7	-0.4	24.8	18.0	12.9	-23.4
4. 3.0 T 18% P	47.9	26.6	32.0	52.7	15.9	-5.9
5. 5.0 T 0% P	36.8	-2.6	25.9	23.6	10.9	-35.1
6. 5.0 T 30% P	53.7	42.1	38.9	85.5	14.8	-11.9
7. HadCM2 2010-2039	52.2	38.0	31.8	51.5	20.4	21.2
8. HadCM2 2050-2079	55.7	47.2	36.8	75.5	18.9	12.0
9. HadCM2 2080-2099	67.6	78.9	47.5	126.6	20.1	19.3
10. PCM 2010-2039	35.7	-5.6	19.5	-7.0	16.2	-3.9
11. PCM 2050-2079	32.9	-13.0	19.6	-6.6	13.3	-21.0
12. PCM 2080-2099	28.5	-24.8	17.1	-18.6	11.4	-32.5
Historical (1921-1993)	37.8	0.0	21.0	0.0	16.8	0.0

Table A.12. Drought year overall water quantities and changes

Climate scenario	Annual Quantity (MAF)	Annual Change (%)	October-March Quantity (MAF)	October-March Change (%)	April-September Quantity (MAF)	April-September Change (%)
1. 1.5 T 0% P	23.6	-0.6	12.3	8.7	11.3	-9.0
2. 1.5 T 9% P	26.5	11.9	14.2	25.5	12.3	-0.5
3. 3.0 T 0% P	23.3	-1.8	13.1	15.5	10.2	-17.7
4. 3.0 T 18% P	29.2	23.2	17.2	51.7	12.0	-2.9
5. 5.0 T 0% P	22.7	-4.3	13.6	20.1	9.1	-26.6
6. 5.0 T 30% P	32.4	36.8	20.8	84.0	11.6	-6.3
7. HadCM2 2010-2039	32.4	36.9	17.3	52.8	15.1	22.3
8. HadCM2 2050-2079	34.3	44.9	20.1	78.0	14.2	14.6
9. HadCM2 2080-2099	40.9	72.5	25.9	128.9	15.0	21.1
10. PCM 2010-2039	22.6	-4.5	10.5	-7.4	12.2	-1.8
11. PCM 2050-2079	20.8	-12.1	10.3	-8.7	10.5	-15.3
12. PCM 2080-2099	18.2	-23.3	9.0	-20.6	9.2	-25.8
Historical (drought years)	23.7	0.0	11.3	0.0	12.4	0.0

Regional analyses (Table A.13, a-c) indicate that southern regions are more sensitive to climate changes under HadCM2 scenarios because the South could see a higher precipitation increase than the North. Under HadCM2 2080-2099 scenario, southern regions (regions 3 and 4) have increased water availability even in the dry season. Under PCM scenarios, water availability decreases for all seasons in all CALVIN regions. No significant spatial trend was found for PCM scenarios.

Table A.13a. Regional analysis of overall annual water quantities and changes (%)

Region	Historical annual (TAF)	Climate change scenario: 3.0 T 0% P	5.0 T 0% P	5.0 T 30% P	HadCM2 2080-2099	PCM 2080-2099
1	10576	0.1	0.3	42.0	57.7	-21.9
2	14002	0.5	-1.1	45.6	77.2	-25.7
3	7078	-0.2	-6.5	38.6	92.0	-26.9
4	6568	-0.1	-0.8	36.9	91.8	-18.1
5[a]	-406	53.6	83.2	14.5	-89.7	87.1
Statewide	37818	-0.4	-2.6	42.1	78.9	-24.8

a. Only rim inflows and surface reservoir evaporations are taken into account in region 5.

Table A.13b. Regional analysis of overall wet season water quantities and changes (%)

Region	Historical October-March (TAF)	Climate change scenario				
		3.0 T 0% P	5.0 T 0% P	5.0 T 30% P	HadCM2 2080-2099	PCM 2080-2099
1	6972	14.0	17.8	70.1	92.9	-17.9
2	8635	20.1	23.0	85.5	129.0	-19.7
3	2866	26.6	36.1	109.6	156.3	-16.3
4	2604	13.3	28.0	92.3	162.7	-13.6
5[b]	-100	45.5	48.6	-112.2	-230.2	121.9
Statewide	20977	18.0	23.6	85.5	126.6	-18.6

a. Only rim inflows and surface reservoir evaporations are taken into account in region 5.

Table A.13c. Regional analysis of overall dry season water quantities and changes (%)

Region	Historical April-September (TAF)	Climate change scenario				
		3.0 T 0% P	5.0 T 0% P	5.0 T 30% P	HadCM2 2080-2099	PCM 2080-2099
1	3603	-26.6	-33.6	-12.4	-10.4	-29.7
2	5367	-31.2	-39.8	-18.5	-6.1	-35.3
3	4212	-18.3	-35.5	-9.7	48.2	-34.1
4	3964	-9.0	-19.7	0.4	45.3	-21.1
5[a]	-306	56.3	94.5	55.8	-44.0	75.8
Statewide	16841	-23.4	-35.1	-11.9	19.3	-32.5

a. Only rim inflows and surface reservoir evaporations are taken into account in region 5.

Figure A.6 (a-c) shows annual and seasonal exceedence probabilities of statewide total water quantities for CALVIN, based on the 72 year 1922-1993 historical hydrology. In the annual case, HadCM2 2080-2099 and PCM 2080-2099 form the upper and lower exceedence probability curves. The averaged annual overall water quantity could be as high as 156.2 MAF under the HadCM2 2080-2099 scenario, and as low as 9.5 MAF under the PCM 2080-2099 scenario. In the dry season, HadCM2 2010-2039 and uniform incremental 5.0 T 0% P form the upper and lower curves with a range of annual quantities from 30.6 MAF to 2.6 MAF. HadCM2 2080-2099 and PCM 2080-2099 in the wet season, varying from 127.3 MAF to 5.3 MAF per year, defined the upper and lower exceedence probability.

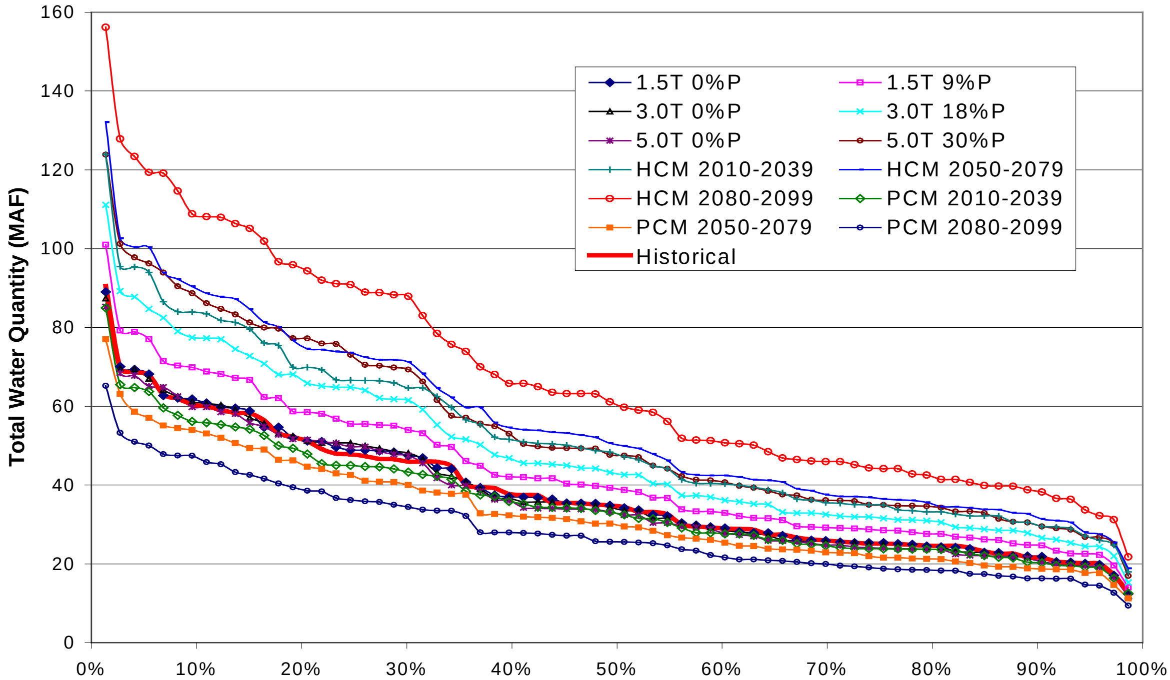

Figure A.6a. Annual exceedence probability

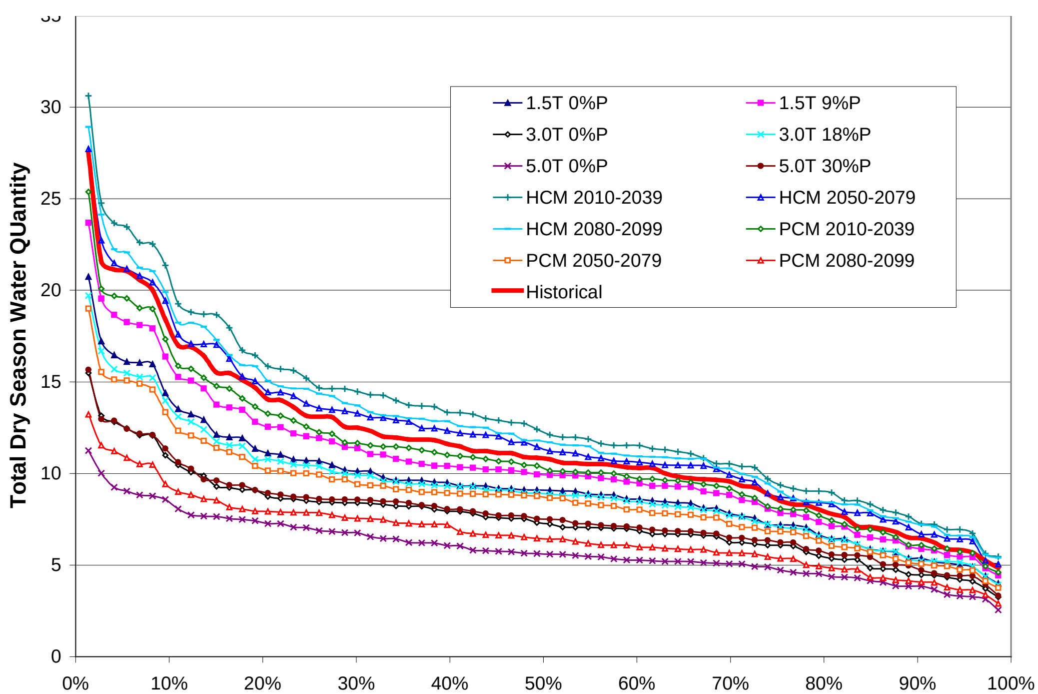

Figure A.6b. Dry season exceedence probability

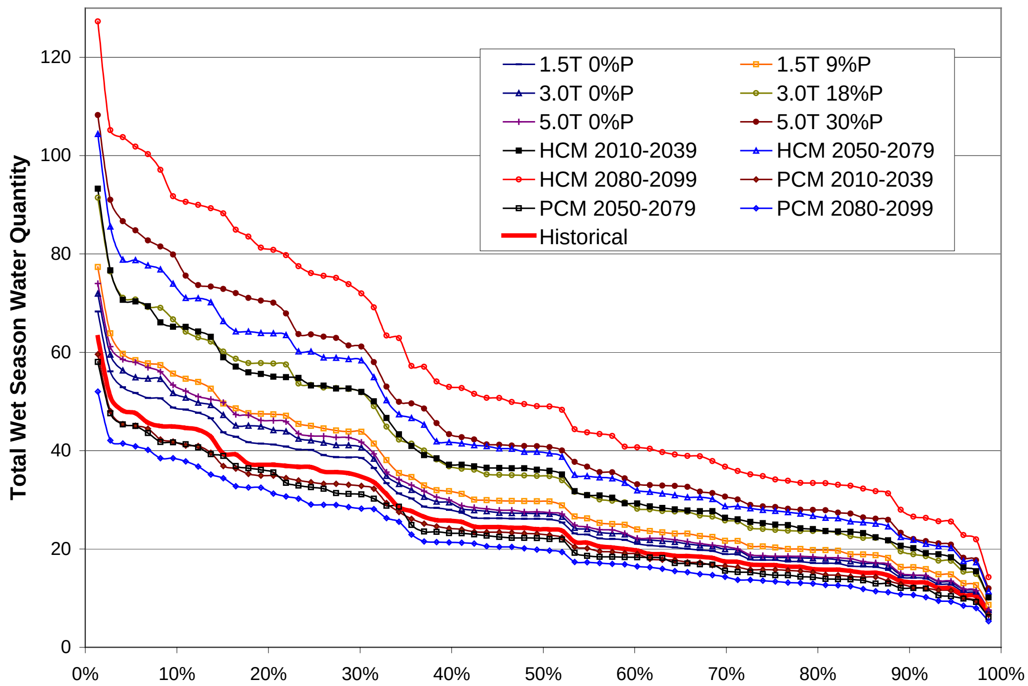

Figure A.6c. Wet season exceedence probability

A.6 Estimated Changes in Water Supply Availability

Accumulated estimation of changes in water supply with climate change requires the use of operations models of facilities and operating policies. However, before this can be done (using the CALVIN model), it is possible to estimate changes in water available for water supply management from climate changes. To do this we assume (1) all changes in dry season inflows directly affect water deliveries (because water is most easily managed during the dry season); (2) increases in wet season surface inflows are lost because of low water demand and low surface storage flexibility resulting from flood control; and (3) changes in wet season groundwater inflows directly affect water supply availability because they directly affect groundwater storage. Because there is likely to be more wet season storage flexibility than is assumed here, the resulting estimates are likely to be more dire than more realistic results from operations modeling.

Table A.14 shows the results of water availability analyses. On average, water availability decreases for all 12 climate scenarios except the three HadCM2 ones, in which water availability increases even in the dry season. For the three uniform precipitation and temperature increase scenarios (1.5 T 9% P, 3.0 T 18% P, and 5.0 T 30% P), actual water availability decreases even though overall water quantities increase as shown in the last section. In drought years, water

Table A.14. Raw water availability estimates and changes (without operational adaptation, in MAF)

Climate scenario	Average annual water availability: Volume (MAF)	Average annual water availability: Change (MAF) (%)	Drought year annual water availability: Volume (MAF)	Drought year annual water availability: Change (MAF) (%)
1. 1.5 T 0% P	35.7	-2.1 (-5.5)	22.5	-1.2 (-5.1)
2. 1.5 T 9% P	37.7	-0.1 (-0.4)	23.7	0.0 (0.0)
3. 3.0 T 0% P	33.7	-4.1 (-10.9)	21.3	-2.4 (-9.9)
4. 3.0 T 18% P	37.1	-0.8 (-2.0)	23.4	-0.2 (-1.0)
5. 5.0 T 0% P	31.6	-6.2 (-16.5)	20.1	-3.6 (-15.1)
6. 5.0 T 30% P	36.2	-1.6 (-4.3)	23.1	-0.6 (-2.5)
7. HadCM2 2010-2039	41.9	4.1 (10.8)	26.7	3.0 (12.8)
8. HadCM2 2050-2079	40.5	2.7 (7.2)	25.9	2.2 (9.4)
9. HadCM2 2080-2099	42.4	4.6 (12.1)	27.2	3.5 (14.7)
10. PCM 2010-2039	35.7	-2.1 (-5.6)	22.6	-1.1 (-4.5)
11. PCM 2050-2079	32.9	-4.9 (-13.0)	20.8	-2.9 (-12.1)
12. PCM 2080-2099	28.5	-9.4 (-24.8)	18.2	-5.5 (-23.3)
Historical	37.8	0.0 (0.0)	23.7	0.0 (0.0)

availability decreases significantly for all 12 scenarios. These conclusions are important to identify potential water supply problems. If the huge amount of increased inflow in the wet season cannot be stored and effectively managed, dry season water supply could decrease significantly even though overall annual water quantity increases. Effective management of wet season groundwater could moderate dry season water supply problems.

A.7 The Importance of More Complete Hydrologic Representation

Table A.15 compares the changes of rim inflows with those of overall water availability under the 12 climate scenarios. Overall water availability decreases more significantly than rim inflows under temperature increase with no more precipitation scenarios, and increases less significantly than rim inflows under temperature increase with more precipitation scenarios partly because reservoir evaporations were accounted for in the overall water availability but also because the increase in rainfall is applied to both wet and dry seasons. Under all the GCM scenarios, overall water availability increases more significantly or decreases less significantly than rim inflows. Moreover, overall water availability shows a relatively moderate shift of water from dry season to wet season compared with the seasonal shift of rim inflows. Considering that most of the wet season groundwater inflows are stored for dry season consumption, as shown in column (8) of the table, the sum of dry season overall water availability plus wet season groundwater inflows

Table A.15. Comparison of water quantity with different hydrologic components (MAF/yr)

	Annual		October-March			April-September		
	Rim inflow	Overall	Rim inflow	Overall	Overall — groundwater inflows	Rim inflow	Overall	Overall + wet season groundwater inflows
Climate scenario	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
1. 1.5 T 0% P	28.6	35.8	16.4	23.1	19.5	12.2	14.9	18.5
2. 1.5 T 9% P	32.4	37.8	18.7	26.4	22.6	13.7	16.6	20.4
3. 3.0 T 0% P	28.5	33.9	18.2	24.8	21.2	10.3	12.9	16.5
4. 3.0 T 18% P	36.2	37.2	23.3	32.0	28.0	12.8	15.9	19.9
5. 5.0 T 0% P	27.9	31.9	19.5	25.9	22.3	8.5	10.9	14.5
6. 5.0 T 30% P	40.6	36.5	28.9	38.9	34.6	11.7	14.8	19.1
7. HadCM2 2010-2039	38.5	42.0	22.0	31.8	27.6	16.5	20.4	24.6
8. HadCM2 2050-2079	41.3	40.7	25.8	36.8	32.4	15.5	18.9	23.3
9. HadCM2 2080-2099	49.8	42.6	33.3	47.5	42.5	16.6	20.1	25.2
10. PCM 2010-2039	26.5	37.0	13.2	19.5	16.1	13.2	16.2	19.6
11. PCM 2050-2079	24.4	34.0	13.7	19.6	16.3	10.7	13.3	16.6
12. PCM 2080-2099	21.1	31.8	12.2	17.1	14.0	8.9	11.4	14.5
Historical (MAF)	28.2	37.8	14.2	21.0	17.4	14.0	16.8	20.4

decreases much less significantly than both rim inflows and overall water availability in the dry season under all the uniform incremental and PCM scenarios (when the dry season experiences serious water decreases). This further indicates that groundwater inflow and other components of hydrologic change help to dampen overall fluctuations in water availability.

A.8 Further Comparative Changes

Climate-induced changes in water supply availability are compared with estimated changes in urban and agriculture demands from 2020 to year 2100. Table A.16 shows the comparative changes of overall water supply and urban and agriculture water demands.

Table A.16. Comparative changes of water availability and demands (MAF/yr)

Climate scenario	Availability change	Water demands changes 2020-2100		
		Overall	Urban	Agriculture
1. 1.5 T 0% P	-2.1	5.8	8.2	-2.7
2. 1.5 T 9% P	-0.1	5.8	8.2	-2.7
3. 3.0 T 0% P	-4.1	5.8	8.2	-2.7
4. 3.0 T 18% P	-0.8	5.8	8.2	-2.7

Table A.16. Comparative changes of water availability and demands (MAF/yr) (cont.)

Climate scenario	Availability change	Water demands changes 2020-2100		
		Overall	Urban	Agriculture
5. 5.0 T 0% P	-6.2	5.8	8.2	-2.7
6. 5.0 T 30% P	-1.6	5.8	8.2	-2.7
7. HadCM2 2010-2039	4.1	5.8	8.2	-2.7
8. HadCM2 2050-2079	2.7	5.8	8.2	-2.7
9. HadCM2 2080-2099	4.6	5.8	8.2	-2.7
10. PCM 2010-2039	-2.1	5.8	8.2	-2.7
11. PCM 2050-2079	-4.9	5.8	8.2	-2.7
12. PCM 2080-2099	-9.4	5.8	8.2	-2.7
Historical	0.0	0.0	0.0	0.0

A.9 Further Research

The following research would help us to better understand and estimate climate change impacts on California's hydrology and water supplies:

1. Because current index basins are located on the north and middle Sierra Nevada, more index basins south of the delta, along the coast, and in the Central Valley floor would be useful.

2. Better ET representation in index basins and the Central Valley floor would be helpful.

3. Groundwater inflows and management can have an important role in moderating climate change effects and need further study.

4. Expansion and modification of existing storage facilities and their operation might be necessary to deal with changed timing pattern of rim inflows.

A.10 Conclusions

Streamflow changes of the six index basins and the effects of statewide temperature shifts and precipitation changes on CALVIN region hydrologies are mapped to construct a distributed hydrologic representation of different climate change scenarios for the CALVIN water management model. The hydrologic inflow results indicate that, under most climate change scenarios, California water quantity is expected to increase in the winter but decrease in the spring and summer. Among the GCM scenarios, HadCM2 scenarios result in increased water quantity and PCM scenarios indicate decreased water quantity. Regional analyses indicate the

South is more sensitive to climate change and tends to get wetter faster than the North, but the South only accounts for a very small portion of water quantities compared to the North. Groundwater and local surface water accretion account for an important portion of total water quantity. Unlike increased winter rim inflows and local surface water accretions that would be lost if not stored in surface reservoirs, increased groundwater inflows would be stored in groundwater basins. For this reason, groundwater management could become more important for adaptation to climate change. In addition, expansion of existing storage reservoirs might be necessary to deal with changed seasonal timing of rim inflows. Demand management is another important option to consider. Water availability changes are different from those of overall water quantity changes because increased wet season surface inflows are likely to be largely lost in water availability analyses. On average, water availability decreases for all 12 climate change scenarios except the HadCM2 ones, even though the uniform temperature and precipitation incremental scenarios show increased overall water quantities. This analysis further stresses the importance of groundwater and reservoir management.

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Table A. Rim inflow changes for each CALVIN rim inflow location (%)

	Trinity River			Clear Creek			Sacramento River			Stony Creek		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	-3.5	13.9	-20.3	-1.1	-0.4	-2.7	1.1	13.1	-17.8	-0.9	-0.3	-2.2
2	8.9	29.7	-11.1	9.3	10.7	5.8	14.3	29.0	-8.8	8.8	10.3	5.8
3	-6.3	25.9	-37.3	-1.3	-0.7	-2.8	2.6	24.7	-32.2	-1.3	-0.8	-2.2
4	18.0	60.7	-23.3	19.3	21.5	14.0	29.3	59.5	-18.3	18.1	20.4	13.4
5	-7.8	32.7	-47.0	-1.4	-0.8	-2.8	3.6	31.6	-40.4	-1.3	-0.8	-2.2
6	31.8	95.4	-29.7	32.9	36.1	25.2	49.0	94.4	-22.4	30.8	34.3	23.9
7	22.3	46.9	-1.5	18.8	20.5	14.7	28.3	46.0	0.4	17.3	18.9	14.2
8	26.7	69.4	-14.5	22.3	31.3	0.6	37.2	68.2	-11.7	20.6	30.3	1.0
9	44.7	112.9	-21.2	38.7	51.3	8.3	62.5	112.7	-16.4	36.7	50.6	8.7
10	-8.2	-9.5	-6.9	-6.4	-9.0	-0.1	-9.1	-10.5	-6.8	-6.1	-8.3	-1.8
11	-16.4	-5.4	-27.1	-11.0	-11.4	-9.9	-14.0	-6.7	-25.5	-7.8	-7.2	-9.1
12	-25.9	-13.3	-38.1	-15.9	-19.3	-7.5	-22.8	-15.2	-34.7	-14.2	-15.5	-11.4
Historical[b]	1217	598	619	263	186	77	5525	3379	2147	396	265	131

a. 12 climate change scenarios are introduced on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Cottonwood Creek			Lewiston Lake Inflow			M & S Fork Yuba River			Feather River		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	-0.8	-0.2	-2.8	-1.2	23.4	-25.4	-1.3	16.0	-25.2	4.1	22.9	-18.6
2	9.6	10.7	5.9	12.8	41.1	-15.0	13.7	34.4	-14.7	17.8	40.4	-9.5
3	-1.1	-0.5	-2.9	-4.0	37.5	-44.7	-2.8	27.8	-44.9	5.0	36.9	-33.8
4	19.6	21.3	14.2	24.4	78.8	-29.2	27.6	68.7	-29.1	33.6	77.6	-19.9
5	-1.1	-0.6	-2.9	-6.5	42.6	-54.8	-4.4	32.5	-55.2	4.0	42.4	-42.5
6	33.2	35.7	25.5	39.8	116.9	-35.9	46.4	106.3	-36.1	52.1	115.4	-24.8
7	18.6	19.7	14.9	39.4	71.3	8.1	41.8	65.7	9.0	37.9	69.3	-0.2
8	23.8	31.0	1.0	47.2	102.3	-7.1	54.7	99.1	-6.5	49.5	100.7	-12.6
9	40.9	51.1	8.6	69.7	159.9	-19.0	84.0	158.5	-18.6	79.4	159.6	-17.9
10	-6.6	-8.9	0.4	-5.1	-4.9	-5.2	-5.5	-5.6	-5.2	-6.4	-6.0	-6.8
11	-9.8	-9.8	-9.8	-15.5	2.2	-32.9	-17.3	-6.0	-32.8	-10.9	1.5	-26.0
12	-15.3	-17.8	-7.2	-29.5	-10.8	-47.9	-32.5	-21.3	-47.9	-22.5	-11.5	-35.8
Historical[b]	554	421	133	46	23	23	426	247	179	3900	2137	1763

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	N. and M. Forks American River			South Fork American River			Cache Creek			Putah Creek		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	-1.6	15.0	-23.3	-0.5	21.9	-25.1	-1.2	-0.6	-2.5	-0.4	0.1	-3.2
2	13.4	33.6	-13.1	13.1	39.4	-15.5	8.7	10.1	5.8	10.2	11.0	5.6
3	-2.9	26.0	-40.8	-1.6	35.3	-41.8	-1.5	-1.0	-2.6	-0.6	-0.2	-3.3
4	27.5	67.6	-25.3	25.6	76.0	-29.3	18.2	20.3	13.8	20.5	21.6	13.9
5	-4.4	30.5	-50.1	-2.9	40.6	-50.4	-1.6	-1.1	-2.6	-0.7	-0.3	-3.3
6	46.7	105.5	-30.6	42.4	113.8	-35.5	31.2	34.3	24.7	34.4	35.8	25.3
7	41.1	65.9	8.6	33.9	68.6	-4.0	17.9	19.5	14.4	18.4	19.1	13.6
8	53.1	97.6	-5.3	44.4	98.4	-14.5	21.3	30.8	1.3	26.0	30.4	-0.6
9	80.3	153.4	-15.7	70.1	155.6	-23.1	36.5	49.5	8.8	45.4	51.7	6.4
10	-5.4	-5.9	-4.8	-7.2	-5.9	-8.6	-5.6	-8.0	-0.4	-7.6	-9.0	0.8
11	-18.5	-8.8	-31.2	-15.6	-1.2	-31.4	-8.8	-8.8	-8.9	-9.1	-8.9	-10.8
12	-33.3	-24.2	-45.2	-29.7	-14.4	-46.4	-14.4	-16.9	-9.1	-14.7	-16.6	-2.7
Historical[b]	1374	780	594	1311	684	627	499	339	160	372	320	52

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	North Fork Yuba River			Calaveras River			Mokelumne River			Cosumnes River		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	-0.1	24.0	-27.0	-1.1	-0.6	-3.0	6.0	20.1	-4.9	3.8	16.4	-21.9
2	14.0	41.5	-16.6	9.3	10.3	5.5	20.5	37.4	7.5	19.5	34.3	-10.6
3	-1.6	38.6	-46.3	-1.4	-0.9	-3.1	6.0	32.5	-14.3	5.2	28.2	-41.6
4	26.2	79.4	-33.1	19.2	20.7	13.6	35.9	72.0	8.2	37.1	68.0	-26.0
5	-3.4	44.1	-56.3	-1.5	-1.0	-3.1	-2.2	36.8	-32.2	4.4	32.6	-53.1
6	42.3	117.4	-41.4	32.8	34.9	24.7	44.3	107.0	-4.0	58.4	104.1	-34.9
7	35.8	70.9	-3.4	18.4	19.9	13.1	50.8	65.7	39.3	46.2	66.6	4.4
8	46.5	102.6	-16.0	24.1	30.7	-0.7	63.2	93.1	40.3	64.2	99.8	-8.3
9	72.9	162.3	-26.7	40.6	49.8	6.2	103.5	147.2	69.8	99.9	158.3	-19.2
10	-6.7	-5.0	-8.6	-6.5	-8.2	-0.2	-5.3	-5.3	-5.3	-5.9	-5.1	-7.6
11	-14.0	3.7	-33.6	-10.0	-9.9	-10.3	-11.9	-2.9	-18.8	-12.1	-2.9	-31.0
12	-28.1	-9.5	-48.9	-14.7	-17.7	-3.8	-26.7	-15.3	-35.4	-27.5	-19.2	-44.4
Historical[b]	1213	639	574	154	121	33	681	296	385	366	245	120

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Deer Creek			Dry Creek			French Dry Creek			Greenhorn Creek and Bear River		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	-0.8	-0.3	-3.1	-1.0	-0.5	-3.5	-1.2	-0.6	-2.5	-1.0	15.8	-24.5
2	9.7	10.7	5.6	9.5	10.4	5.5	8.8	10.2	5.6	13.9	34.1	-14.3
3	-1.1	-0.6	-3.2	-1.3	-0.8	-3.6	-1.5	-1.0	-2.6	-1.2	27.4	-41.3
4	20.0	21.4	13.9	19.6	20.8	14.1	18.4	20.7	13.4	28.8	68.1	-26.3
5	-1.1	-0.6	-3.2	-1.4	-0.9	-3.6	-1.6	-1.1	-2.6	-2.1	32.0	-50.0
6	33.9	35.9	25.3	33.4	35.0	25.8	31.6	35.0	24.1	48.6	105.3	-30.9
7	18.9	20.1	13.9	18.7	19.7	13.6	18.2	20.2	13.6	41.2	66.0	6.5
8	25.0	31.1	-0.3	25.0	30.7	-1.8	21.8	31.5	0.1	54.5	98.5	-7.2
9	42.6	51.2	6.9	42.0	49.8	5.3	37.2	50.3	7.4	84.9	157.5	-16.9
10	-7.0	-8.9	1.1	-6.5	-8.2	1.4	-6.2	-8.5	-1.0	-5.1	-5.4	-4.6
11	-10.5	-10.5	-10.9	-10.1	-9.7	-12.5	-10.1	-10.1	-10.0	-16.3	-5.0	-32.0
12	-15.6	-18.5	-3.4	-14.3	-17.4	0.3	-15.3	-18.6	-8.0	-31.4	-21.0	-46.0
Historical[b]	68	55	13	81	67	14	133	92	41	418	244	174

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Kelly Ridge			Stanislaus River			San Joaquin River			Merced River		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	-0.9	0.0	-1.7	6.5	21.5	-2.9	2.2	19.8	-7.1	8.2	23.9	0.6
2	8.8	12.2	5.9	20.8	38.7	9.6	16.0	36.7	5.1	22.5	41.1	13.5
3	-1.0	-0.1	-1.8	6.3	34.5	-11.4	-0.4	31.5	-17.2	8.2	38.1	-6.3
4	18.4	24.5	13.2	35.8	74.0	11.8	27.1	69.9	4.5	37.8	78.0	18.3
5	-1.0	-0.2	-1.8	-3.2	38.9	-29.7	-10.3	35.1	-34.3	-3.2	42.9	-25.5
6	31.6	41.5	23.2	42.2	109.1	0.1	30.4	102.7	-7.7	42.3	114.1	7.5
7	19.1	24.2	14.7	51.3	67.6	41.1	47.1	65.3	37.5	53.3	70.6	44.9
8	16.9	35.6	1.1	63.5	96.2	43.0	56.1	92.1	37.2	66.1	101.6	48.9
9	32.8	60.3	9.4	103.8	151.3	74.0	92.3	143.3	65.5	107.7	159.2	82.8
10	-8.0	-13.3	-3.5	-4.9	-4.9	-5.0	-5.3	-4.7	-5.6	-4.3	-4.3	-4.3
11	-13.8	-19.1	-9.3	-10.5	0.8	-17.6	-13.4	-0.7	-20.1	-8.7	5.4	-15.5
12	-21.3	-28.3	-15.4	-25.4	-12.1	-33.7	-29.0	-13.5	-37.2	-23.3	-7.7	-30.8
Historical[b]	126	58	68	1057	408	649	1681	580	1101	922	301	621

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Fresno River			Chowchilla River			Clocal Inflow to New Don Pedro			Tuolumne River		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	-1.8	-1.2	-2.8	-1.5	-1.0	-3.3	-2.8	14.2	-22.7	-0.6	73.9	-16.2
2	8.1	9.4	5.9	8.6	9.5	5.6	10.4	29.7	-12.1	15.1	102.9	-3.4
3	-2.1	-1.6	-2.9	-1.9	-1.5	-3.4	-4.8	26.3	-41.2	-0.8	170.3	-36.8
4	17.5	19.4	14.2	18.2	19.4	14.1	21.2	60.5	-24.9	30.7	254.0	-16.3
5	-2.1	-1.7	-2.9	-2.0	-1.5	-3.4	-6.2	32.6	-51.6	-0.8	293.7	-62.7
6	30.4	33.1	25.6	31.4	33.1	25.8	36.3	93.9	-31.2	53.3	500.4	-40.8
7	17.9	19.7	14.8	18.0	19.3	13.9	30.4	46.9	11.2	45.9	145.2	25.0
8	20.1	30.7	1.4	23.1	30.4	-0.6	35.7	69.4	-3.8	60.7	259.4	18.9
9	33.1	46.8	8.8	37.8	47.4	6.5	54.3	113.2	-14.8	101.1	477.6	22.0
10	-3.9	-6.7	0.9	-4.9	-6.8	1.5	-6.9	-8.6	-4.9	-0.4	18.9	-4.5
11	-9.1	-9.1	-9.2	-8.9	-8.2	-11.2	-15.3	-1.6	-31.3	-19.1	17.9	-26.8
12	-13.0	-16.5	-6.8	-12.4	-15.6	-1.8	-26.1	-9.9	-45.0	-35.2	31.0	-49.1
Historical[b]	84	54	30	69	53	16	618	333	285	747	130	617

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Cherry and Elnor			Santa Clara Valley Local			Kern River			Kaweah River		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	-1.5	16.9	-9.1	-0.1	0.3	-3.0	1.9	16.3	-3.9	-1.5	18.6	-10.8
2	12.6	34.1	3.7	11.4	12.2	5.9	15.6	32.8	8.8	12.7	35.7	2.1
3	-5.1	45.6	-26.2	-0.2	0.2	-3.0	3.6	44.9	-13.1	-3.3	50.5	-28.1
4	23.3	89.1	-4.0	22.9	24.2	14.5	31.7	85.6	10.1	25.2	93.6	-6.3
5	-7.8	99.3	-52.3	-0.2	0.2	-3.0	5.4	98.1	-31.8	-2.3	109.4	-53.7
6	39.2	196.9	-26.3	38.5	40.3	26.2	52.6	189.3	-2.3	45.9	207.3	-28.3
7	42.0	70.3	30.3	21.5	22.3	15.9	49.2	68.9	41.3	43.0	73.7	28.8
8	54.9	119.5	28.0	28.7	33.0	-0.8	63.3	114.8	42.7	56.2	122.4	25.8
9	89.9	219.8	35.9	50.5	56.7	7.7	113.9	214.8	73.4	95.9	232.6	33.1
10	-1.7	2.6	-3.4	-10.4	-11.9	-0.1	-3.3	1.3	-5.1	-1.9	2.2	-3.7
11	-17.0	-5.4	-21.8	-15.6	-16.1	-12.8	-14.3	-4.2	-18.3	-16.5	-1.9	-23.2
12	-32.5	-9.6	-42.0	-22.0	-24.4	-5.6	-27.4	-8.7	-34.9	-31.8	-6.3	-43.5
Historical[b]	436	128	308	126	110	16	684	196	488	416	131	285

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Tule River			Kings River			Lower Owens Valley — Haiwee			Mono Basin		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	0.3	24.0	-26.2	0.6	17.6	-4.2	-0.6	2.6	-1.7	-2.1	62.8	-13.8
2	14.3	41.3	-15.6	14.2	34.2	8.5	12.7	17.1	11.3	12.8	91.0	-1.4
3	-1.4	38.2	-45.5	-0.6	48.1	-14.5	-1.9	10.1	-5.9	-2.9	145.5	-29.7
4	26.1	78.3	-31.8	26.7	89.4	8.7	24.9	44.2	18.5	26.5	225.5	-9.4
5	-3.7	43.1	-55.8	-3.8	104.5	-34.7	-4.4	32.9	-16.6	-3.7	254.6	-50.4
6	41.3	114.7	-40.2	39.8	198.1	-5.4	38.4	100.4	18.1	44.9	451.4	-28.5
7	36.6	71.2	-2.0	48.0	71.4	41.4	45.0	40.1	46.6	49.0	129.8	34.4
8	47.2	102.8	-14.6	59.2	118.6	42.2	56.2	67.0	52.6	61.0	236.4	29.3
9	72.1	159.7	-25.4	106.1	224.4	72.3	100.0	137.4	87.7	110.8	432.7	52.6
10	-6.3	-4.5	-8.4	-3.7	1.5	-5.2	-3.6	0.5	-4.9	-3.4	16.3	-6.9
11	-13.0	5.1	-33.2	-15.3	-3.0	-18.8	-16.3	-15.9	-16.4	-20.2	6.6	-25.0
12	-27.0	-8.0	-48.1	-29.6	-7.3	-36.0	-30.1	-26.3	-31.3	-36.2	15.5	-45.5
Historical[b]	132	69	62	1594	354	1240	292	72	220	119	18	101

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table A. Rim inflow changes for each CALVIN rim inflow location (%) (cont.)

	Upper Owens		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.
1	-6.5	11.9	-22.0
2	5.7	28.5	-13.5
3	-4.6	33.1	-36.2
4	20.7	73.9	-24.1
5	11.1	75.3	-42.9
6	60.2	164.5	-27.5
7	24.7	60.2	-5.2
8	38.7	104.4	-16.7
9	76.7	193.4	-21.5
10	-5.0	-1.3	-8.2
11	-20.6	-11.8	-28.0
12	-30.3	-18.2	-40.5
Historical[b]	143	66	78

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%)

	Clair Engle Lake — Prosim			Whiskeytown Lake — Dwr_514			Shasta Lake — Dwr_514			Black Butte Lake		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	12.5	52.4	7.4	14.4	40.3	9.2	14.6	39.2	9.4	9.9	22.4	7.1
2	10.1	34.4	7.0	14.3	39.7	9.2	14.5	39.2	9.4	8.6	16.8	6.8
3	25.1	104.7	14.9	28.8	80.6	18.4	29.1	78.5	18.8	19.8	44.8	14.2
4	20.3	68.9	14.0	28.6	79.4	18.4	29.1	78.4	18.8	17.2	33.5	13.6
5	41.8	174.6	24.8	48.1	134.3	30.7	48.5	130.8	31.3	32.9	74.7	23.7
6	33.8	114.8	23.4	47.7	132.3	30.6	48.5	130.7	31.3	28.6	55.9	22.6
7	4.5	-4.4	5.6	12.9	35.3	8.4	13.3	36.0	8.6	5.3	4.0	5.6
8	11.4	18.8	10.4	22.6	62.3	14.6	23.3	62.7	15.0	11.1	15.4	10.2
9	11.1	-8.0	13.6	31.0	84.8	20.2	32.1	86.4	20.7	12.9	10.6	13.4
10	4.0	18.8	2.1	3.9	11.1	2.5	3.9	10.6	2.5	3.0	7.5	2.0
11	15.8	76.5	8.0	14.7	41.3	9.3	14.7	39.5	9.4	11.6	30.0	7.6
12	26.4	133.4	12.7	22.7	64.2	14.4	22.6	61.0	14.6	19.1	51.2	12.0
Historical[b]	29.36	3.33	26.03	10.81	1.81	9.00	80.07	13.87	66.20	2.18	0.39	1.79

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Lake Oroville — Dwr_514			Thermalito Forebay — Dwr_514			Folsom Lake — Dwr_514			Camp Far West Res. — Hec3_Bear		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	38.2	-178.2	18.3	39.0	-181.5	17.8	24.8	-141.2	13.3	12.0	39.0	6.8
2	41.2	-202.9	18.8	42.2	-206.4	18.2	22.7	-118.3	12.9	9.0	23.2	6.3
3	76.5	-356.5	36.7	78.1	-362.9	35.5	49.7	-282.4	26.6	23.9	78.0	13.6
4	82.5	-405.8	37.6	84.3	-412.7	36.4	45.5	-236.7	25.9	18.1	46.4	12.7
5	127.4	-594.1	61.1	130.2	-604.9	59.2	82.8	-470.6	44.3	39.8	130.1	22.6
6	137.5	-676.3	62.6	140.5	-687.8	60.6	75.8	-394.4	43.1	30.1	77.3	21.1
7	43.9	-236.0	18.2	45.0	-239.6	17.5	16.7	-62.7	11.2	2.4	-10.6	4.9
8	72.1	-374.5	31.0	73.8	-380.5	29.9	32.1	-143.0	20.0	8.6	5.0	9.2
9	105.1	-563.7	43.6	107.7	-572.3	42.1	40.4	-154.0	26.9	6.3	-23.1	11.9
10	9.6	-41.8	4.8	9.8	-42.6	4.7	7.3	-44.2	3.7	4.0	14.7	2.0
11	34.5	-146.5	17.8	35.1	-149.5	17.3	27.8	-172.4	13.9	15.9	60.3	7.4
12	50.6	-204.7	27.1	51.5	-209.1	26.4	44.6	-285.5	21.7	27.0	106.6	11.8
Historical[b]	28.01	-2.84	30.84	2.21	-0.24	2.45	21.01	-1.57	22.58	0.91	0.15	0.76

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Clear Lake and Indian Valley			Camanche Res. — Sanjasm_92			Ebmud Aggregate Local Storage			Englebright Lake — Hec3_Yuba		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	14.3	32.5	9.4	21.0	-125.8	10.7	5.1	-1.6	1.0	18.5	37.4	12.3
2	13.8	30.4	9.3	17.2	-83.7	10.0	-40.4	23.9	-1.2	20.5	44.6	12.6
3	28.5	65.0	18.7	42.1	-251.5	21.3	10.2	-3.2	2.0	36.9	74.9	24.6
4	27.5	60.8	18.5	34.3	-167.4	20.1	-80.9	47.8	-2.4	41.0	89.2	25.2
5	47.5	108.3	31.2	70.1	-419.2	35.5	16.9	-5.3	3.3	61.6	124.8	40.9
6	45.8	101.3	30.9	57.2	-279.0	33.4	-134.8	79.6	-3.9	68.3	148.6	42.0
7	11.6	23.6	8.4	8.0	7.8	7.9	-128.7	73.2	-5.5	22.9	55.4	12.3
8	21.0	44.3	14.7	19.6	-48.8	14.8	-156.8	89.8	-6.3	36.9	85.8	20.9
9	28.0	57.2	20.1	19.7	12.4	19.2	-302.7	172.2	-12.8	54.7	132.0	29.4
10	4.0	9.3	2.6	6.7	-45.0	3.0	13.2	-7.1	0.8	4.5	8.3	3.2
11	15.0	35.5	9.5	26.3	-182.3	11.6	65.5	-35.4	3.9	15.9	28.1	11.9
12	23.6	56.6	14.7	43.9	-317.5	18.4	140.3	-76.6	7.9	22.8	37.2	18.1
Historical[b]	57.07	12.11	44.95	4.30	-0.33	4.63	1.17	-1.83	3.00	3.94	0.97	2.97

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Lake Berryesa			Los Vaqueros Res. — Ccwd			New Bullards Bar — Hec3_Yuba			New Hogan Lake — Sanjasm_92		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	13.6	31.8	8.7	1.0	2.2	0.7	12.2	25.8	8.6	5.0	9.2	3.6
2	13.2	30.1	8.7	-4.6	-19.7	-0.2	11.6	23.3	8.5	2.1	-0.2	2.9
3	27.3	63.7	17.4	2.0	4.4	1.3	24.4	51.5	17.2	10.1	18.4	7.2
4	26.4	60.1	17.3	-9.2	-39.5	-0.4	23.1	46.6	16.9	4.2	-0.4	5.8
5	45.5	106.1	29.1	3.4	7.4	2.2	40.6	85.8	28.6	16.8	30.7	12.0
6	44.1	100.2	28.9	-15.4	-65.8	-0.7	38.5	77.6	28.2	7.0	-0.7	9.6
7	11.3	24.1	7.9	-15.6	-62.3	-2.0	9.4	16.4	7.5	-4.0	-19.1	1.2
8	20.3	44.5	13.8	-18.8	-76.0	-2.1	17.2	32.3	13.3	-2.6	-19.4	3.1
9	27.2	58.1	18.9	-36.6	-146.5	-4.6	22.6	39.8	18.0	-9.2	-44.6	3.0
10	3.8	9.1	2.4	1.7	6.3	0.4	3.5	7.6	2.4	2.1	4.9	1.2
11	14.3	34.4	8.8	8.5	31.4	1.8	13.1	29.2	8.8	9.0	21.8	4.6
12	22.4	54.5	13.7	18.0	67.3	3.6	20.7	47.1	13.7	16.4	41.7	7.7
Historical[b]	46.14	9.82	36.32	4.76	1.07	3.68	18.23	3.81	14.42	8.22	2.11	6.12

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Pardee Res. — Sanjasm_92			New Melones Res. — Dwr_514			Swp San Luis Res. — Dwr_514			Del Valle Reservoir — Dwr_514		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	21.9	-152.9	10.7	11.6	27.0	7.5	20.5	50.0	11.9	8.1	37.3	4.8
2	17.7	-102.2	10.0	10.1	20.9	7.2	20.5	50.2	11.9	2.3	-10.6	3.8
3	43.8	-305.8	21.3	23.2	54.0	15.0	40.9	100.0	23.7	16.3	74.6	9.5
4	35.5	-204.5	20.0	20.1	41.7	14.4	41.1	100.5	23.7	4.6	-21.1	7.6
5	73.0	-509.6	35.5	38.6	90.1	25.0	68.2	166.6	39.5	27.1	124.3	15.8
6	59.1	-340.8	33.4	33.5	69.5	24.0	68.5	167.4	39.6	7.7	-35.2	12.6
7	7.9	8.0	7.9	6.2	6.7	6.0	19.0	46.6	10.9	-9.6	-106.0	1.5
8	19.9	-61.0	14.7	13.0	20.9	10.9	33.0	80.8	19.0	-8.1	-113.7	4.1
9	19.6	11.8	19.1	15.1	17.1	14.6	45.6	112.0	26.3	-22.3	-247.6	3.9
10	7.0	-54.5	3.1	3.5	8.9	2.1	5.5	13.5	3.2	3.7	22.5	1.5
11	27.5	-221.0	11.6	13.7	35.4	7.9	20.5	50.0	11.9	15.9	101.0	6.1
12	46.1	-384.5	18.4	22.4	59.9	12.5	31.6	76.8	18.4	29.6	197.0	10.2
Historical[b]	3.90	-0.27	4.16	44.64	9.34	35.30	91.98	20.78	71.20	2.07	0.22	1.86

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Millerton Lake — Dwr_514			Lake Mcclure — Dwr_514			Los Banos Grandes Res. — Dwr_514			Hensley Lake — Dwr_514		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	13.7	35.4	8.7	12.8	33.2	8.5	11.1	27.1	8.6	12.2	31.2	8.3
2	13.1	32.7	8.6	12.1	29.8	8.4	9.0	15.9	7.9	11.4	27.5	8.1
3	27.4	70.7	17.4	25.6	66.3	17.1	22.1	54.1	17.3	24.3	62.4	16.7
4	26.2	65.5	17.1	24.2	59.6	16.8	18.0	31.7	15.9	22.7	54.9	16.3
5	45.7	117.9	29.0	42.7	110.6	28.5	36.8	90.2	28.8	40.5	104.0	27.8
6	43.7	109.2	28.5	40.4	99.4	28.0	29.9	52.9	26.5	37.8	91.5	27.1
7	10.8	24.8	7.6	9.7	20.6	7.5	4.1	-8.0	5.9	8.8	17.7	7.1
8	19.8	47.1	13.4	18.0	40.9	13.2	10.2	2.7	11.3	16.5	36.3	12.6
9	26.1	60.0	18.3	23.5	50.1	17.9	10.1	-17.5	14.3	21.3	43.0	17.0
10	3.9	10.3	2.4	3.6	9.9	2.3	3.5	10.2	2.5	3.5	9.4	2.3
11	14.6	39.1	8.9	13.8	37.8	8.8	13.9	42.1	9.6	13.3	36.4	8.7
12	23.0	62.5	13.8	21.9	61.2	13.7	23.2	74.6	15.4	21.2	59.3	13.5
Historical[b]	18.03	3.39	14.65	33.90	5.85	28.05	0.00	0.00	0.00	2.62	0.44	2.19

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Eastman Lake — Dwr_514			Don Pedro Res. — Dwr_514			Sr-Asf			Sr-Hhr		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	12.8	32.0	8.4	11.5	28.2	7.6	1.0	2.2	0.7	11.8	28.2	7.6
2	11.9	28.1	8.2	10.1	22.1	7.3	-4.7	-20.1	-0.3	10.4	22.2	7.3
3	25.5	64.0	16.8	23.0	56.4	15.1	2.0	4.5	1.3	23.6	56.4	15.2
4	23.7	56.2	16.4	20.2	44.3	14.6	-9.3	-40.2	-0.5	20.7	44.3	14.7
5	42.6	106.7	28.0	38.3	94.0	25.2	3.3	7.4	2.2	39.4	94.0	25.4
6	39.6	93.7	27.3	33.7	73.8	24.3	-15.5	-67.0	-0.9	34.6	73.9	24.5
7	9.1	18.0	7.1	6.5	8.1	6.2	-15.7	-63.4	-2.1	6.6	8.2	6.2
8	17.2	37.1	12.6	13.4	23.1	11.2	-18.9	-77.4	-2.3	13.7	23.2	11.2
9	22.0	43.8	17.0	15.9	20.4	14.9	-36.8	-149.1	-4.9	16.1	20.6	14.9
10	3.7	9.7	2.3	3.5	9.2	2.1	1.7	6.4	0.4	3.6	9.2	2.1
11	14.0	37.4	8.8	13.4	36.4	8.0	8.5	31.9	1.9	13.8	36.4	8.0
12	22.4	61.0	13.7	21.8	61.4	12.5	18.0	68.4	3.7	22.5	61.3	12.6
Historical[b]	2.94	0.54	2.39	57.41	10.89	46.52	7.46	1.65	5.81	13.16	2.68	10.48

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	SR LL — LE			SR — SCV			Tulloch Res. — Sanjasm_92			Lake Isabella		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	11.2	28.0	7.5	1.0	2.2	0.7	12.9	29.5	8.3	10.9	24.6	7.8
2	9.9	22.1	7.3	-5.1	-20.7	-0.4	12.0	25.9	8.1	10.8	23.8	7.8
3	22.4	56.1	15.0	2.0	4.4	1.3	25.8	59.0	16.6	21.9	49.2	15.6
4	19.8	44.2	14.5	-10.2	-41.3	-0.9	24.0	51.9	16.3	21.5	47.6	15.5
5	37.3	93.5	25.0	3.4	7.4	2.2	43.0	98.3	27.7	36.5	82.0	26.1
6	33.0	73.7	24.2	-17.0	-68.9	-1.5	40.0	86.5	27.1	35.9	79.3	25.9
7	6.6	8.4	6.2	-17.0	-65.0	-2.7	9.2	16.7	7.2	9.5	20.2	7.0
8	13.3	23.4	11.1	-20.5	-79.4	-3.0	17.4	34.4	12.7	16.8	36.4	12.3
9	16.0	21.0	14.9	-39.9	-152.9	-6.2	22.3	40.7	17.2	22.9	48.8	16.9
10	3.4	9.1	2.1	1.9	6.5	0.5	3.7	8.9	2.3	3.0	6.9	2.1
11	12.9	36.1	7.9	9.2	32.6	2.2	14.2	34.4	8.6	11.3	25.8	7.9
12	21.0	60.8	12.4	19.4	70.0	4.3	22.6	56.0	13.3	17.5	40.5	12.3
Historical[b]	13.63	2.43	11.20	7.04	1.62	5.42	6.87	1.49	5.38	20.59	3.84	16.75

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Lake Kaweah			Lake Success			Pine Flat Res.			Silverwood Lake — Dwr_514		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	10.3	29.1	8.8	9.2	23.3	7.6	11.2	28.6	7.4	11.6	33.4	7.1
2	10.2	28.2	8.8	8.7	20.4	7.4	10.1	23.7	7.1	8.8	19.6	6.6
3	20.7	58.1	17.6	18.4	46.6	15.3	22.3	57.2	14.7	23.2	66.9	14.3
4	20.4	56.4	17.5	17.5	40.7	14.9	20.1	47.4	14.2	17.6	39.2	13.2
5	34.4	96.9	29.4	30.7	77.6	25.5	37.2	95.3	24.5	38.7	111.5	23.8
6	34.0	94.0	29.2	29.1	67.9	24.8	33.6	78.9	23.7	29.3	65.4	21.9
7	9.1	24.2	7.9	7.0	12.9	6.4	7.1	11.9	6.0	2.4	-9.8	4.9
8	16.1	43.4	13.9	13.0	26.7	11.5	13.9	28.0	10.9	8.4	3.4	9.4
9	22.0	58.2	19.1	17.0	31.3	15.4	17.2	29.3	14.5	6.2	-21.5	11.9
10	2.8	8.1	2.4	2.6	7.1	2.1	3.3	9.0	2.1	3.9	12.6	2.1
11	10.5	30.4	8.9	9.9	27.3	8.0	12.6	35.3	7.7	15.4	52.0	7.9
12	16.4	47.6	13.9	15.7	44.6	12.5	20.4	58.6	12.1	26.2	92.1	12.7
Historical[b]	1.14	0.09	1.06	4.91	0.49	4.42	13.02	2.33	10.69	1.37	0.23	1.13

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Lake Perris — DWR_514			Pyramid Lake — DWR_514			Castaic Lake — DWR_514			Eastside		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	19.0	73.7	11.2	12.4	49.4	7.0	15.2	51.3	8.9	21.1	77.8	12.3
2	17.6	63.7	10.9	8.5	22.4	6.4	12.7	36.9	8.5	19.2	65.6	11.9
3	38.0	147.4	22.3	24.8	98.8	14.0	30.4	102.6	17.9	42.3	155.6	24.6
4	35.1	127.5	21.9	16.9	44.8	12.9	25.5	73.7	17.1	38.3	131.3	23.8
5	63.3	245.6	37.2	41.4	164.6	23.4	50.7	171.0	29.8	70.5	259.3	40.9
6	58.5	212.4	36.5	28.2	74.7	21.4	42.5	122.8	28.5	63.9	218.8	39.6
7	13.2	38.5	9.6	-0.2	-33.7	4.7	6.7	4.8	7.1	13.6	35.9	10.1
8	25.2	81.8	17.1	5.5	-18.8	9.1	15.4	29.7	12.9	26.6	80.5	18.2
9	32.0	94.0	23.1	0.2	-77.1	11.4	16.6	13.6	17.1	33.0	88.0	24.4
10	5.5	22.5	3.1	4.4	20.4	2.1	4.8	17.6	2.5	6.2	24.2	3.4
11	21.0	87.3	11.5	17.7	85.5	7.8	18.6	70.8	9.5	23.9	94.3	12.9
12	33.6	143.3	17.9	30.7	155.1	12.6	30.8	121.6	15.0	38.5	156.0	20.2
Historical[b]	8.28	1.04	7.24	5.74	0.73	5.01	7.70	1.14	6.56	13.64	1.84	11.80

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Grant Lake			Laa Storage			Lake Crowley			Lk Mathews		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	11.5	28.3	8.5	7.7	15.9	5.3	9.3	20.1	6.4	25.1	109.0	12.3
2	12.5	31.7	9.0	7.1	14.0	5.0	9.4	20.7	6.4	22.4	91.3	11.9
3	23.1	56.6	16.9	15.4	31.9	10.5	18.5	40.2	12.8	50.3	218.1	24.6
4	25.1	63.3	18.0	14.2	28.0	10.0	18.9	41.3	12.9	44.9	182.6	23.8
5	38.5	94.3	28.2	25.7	53.1	17.5	30.9	67.0	21.3	83.8	363.5	41.0
6	41.8	105.5	30.0	23.6	46.7	16.7	31.4	68.9	21.5	74.8	304.3	39.6
7	13.5	35.8	9.4	5.3	9.0	4.1	9.0	20.1	6.0	15.2	48.1	10.1
8	22.0	57.4	15.5	10.1	18.5	7.6	15.4	34.2	10.4	30.4	110.1	18.2
9	32.3	85.7	22.4	12.7	21.9	10.0	21.6	48.2	14.5	36.9	118.2	24.4
10	2.9	6.8	2.1	2.2	4.8	1.5	2.5	5.3	1.7	7.5	34.1	3.4
11	10.3	24.0	7.8	8.6	18.6	5.6	9.1	19.5	6.3	28.9	133.2	12.9
12	15.1	34.1	11.5	13.8	30.3	8.8	13.9	29.6	9.7	46.9	220.8	20.2
Historical[b]	3.81	0.59	3.21	2.94	0.67	2.26	6.09	1.28	4.81	8.51	1.13	7.38

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table B. Evaporation changes for each CALVIN surface reservoir (%) (cont.)

	Lk Skinner			Mono Lake			Salton Sea		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	22.1	85.4	12.3	14.0	29.4	9.2	9.7	17.4	6.7
2	20.0	71.9	11.9	15.4	33.2	9.8	8.8	15.3	6.3
3	44.2	170.8	24.6	28.1	58.8	18.4	19.4	34.7	13.5
4	39.9	143.8	23.8	30.7	66.3	19.6	17.6	30.5	12.6
5	73.7	284.7	41.0	46.8	98.0	30.7	32.3	57.9	22.4
6	66.6	239.7	39.7	51.2	110.5	32.7	29.3	50.8	21.0
7	14.0	38.9	10.1	16.8	38.0	10.2	6.3	9.7	4.9
8	27.6	87.7	18.2	27.3	60.6	16.9	12.2	20.1	9.2
9	34.0	95.4	24.4	40.2	90.8	24.4	15.2	23.7	11.9
10	6.5	26.6	3.4	3.5	7.0	2.3	2.9	5.3	1.9
11	25.1	103.8	12.9	12.3	24.6	8.5	10.9	20.3	7.3
12	40.6	171.8	20.2	17.9	34.7	12.6	17.6	33.1	11.7
Historical[b]	5.66	0.76	4.90	68.98	16.45	52.53	828.01	229.72	598.29

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table C. Changes for each CALVIN groundwater basin inflow (%)

	Source_GW-1			Source_GW-2			Source_GW-3			Source_GW-4		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	674.0	19.4	-3.2	7.5	8.8	3.8	123.7	22.2	-3.2	1.9	3.2	0.5
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1347.9	38.9	-6.4	15.0	17.6	7.5	247.4	44.5	-6.4	3.8	6.5	0.9
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	2246.5	64.8	-10.7	25.0	29.3	12.6	412.3	74.1	-10.7	6.4	10.8	1.5
7	1643.1	45.6	-9.6	18.1	20.9	9.9	306.4	54.2	-9.0	5.5	8.5	2.1
8	2104.5	68.2	-2.2	23.5	31.1	1.2	413.9	80.9	-2.6	7.2	12.8	1.0
9	3543.1	113.4	-5.3	41.0	53.2	5.3	725.2	140.8	-5.8	11.7	21.2	1.1
10	-490.1	-16.8	-0.5	-6.9	-8.7	-1.6	-119.4	-23.3	0.8	-1.4	-3.0	0.4
11	-813.9	-23.2	4.2	-11.3	-11.8	-9.6	-209.6	-35.6	8.1	-2.7	-4.5	-0.7
12	-1420.2	-45.4	2.2	-18.8	-22.9	-6.9	-332.4	-62.0	5.9	-4.5	-8.7	0.1
Historical[b]	1.9	55.4	-53.5	402.7	300.1	102.6	11.7	58.3	-46.6	263.1	138.5	124.6

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table C. Changes for each CALVIN groundwater basin inflow (%) (cont.)

	Source_GW-5			Source_GW-6			Source_GW-7			Source_GW-8		
Scenario[a]	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.	Annual	Oct.-Mar.	Apr.-Sep.
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	14.9	12.5	-17.0	2.4	3.7	1.2	2.4	3.9	0.4	0.9	1.5	0.3
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	29.7	25.1	-33.9	4.8	7.5	2.4	4.7	7.7	0.9	1.8	3.1	0.5
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	49.5	41.8	-56.5	8.1	12.4	3.9	7.8	12.9	1.5	3.1	5.1	0.9
7	39.1	30.5	-78.8	5.6	11.3	0.1	6.3	9.6	2.2	3.0	4.4	1.5
8	52.8	46.7	-31.2	7.1	14.7	-0.2	8.7	14.7	1.1	3.8	6.5	1.0
9	90.3	81.1	-35.9	13.0	23.6	2.8	15.1	26.2	1.0	5.8	10.5	0.9
10	-10.4	-10.8	-15.9	-1.6	-2.6	-0.6	-1.6	-3.2	0.4	-0.5	-1.2	0.3
11	-17.9	-14.8	24.5	-4.3	-6.1	-2.5	-2.8	-4.5	-0.8	-1.3	-2.1	-0.4
12	-32.1	-30.6	-11.1	-6.7	-9.6	-3.9	-5.3	-9.5	0.1	-2.2	-4.1	-0.1
Historical[b]	144.9	156.3	-11.4	365.7	178.6	187.1	278.0	155.2	122.9	747.4	386.6	360.8

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table C. Changes for each CALVIN groundwater basin inflow (%) (cont.)

	Source_GW-9			Source_GW-10			Source_GW-11			Source_GW-12		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	149.7	23.1	-3.3	1.9	3.5	0.5	-14.5	-79.3	-2.1	2.3	4.0	0.7
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	299.3	46.2	-6.6	3.8	7.1	1.0	-29.0	-158.6	-4.3	4.7	8.0	1.5
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	498.9	77.1	-11.0	6.3	11.8	1.6	-48.3	-264.3	-7.1	7.8	13.3	2.4
7	468.5	66.6	-17.3	6.7	10.8	3.2	-47.0	-226.0	-12.9	8.2	11.7	4.8
8	626.5	99.9	-10.1	8.4	16.0	2.1	-62.0	-347.8	-7.6	10.2	17.5	3.1
9	1007.3	166.6	-9.0	14.0	28.3	2.0	-97.7	-576.1	-6.6	15.8	28.9	2.8
10	-104.2	-20.9	-3.5	-1.2	-3.2	0.4	8.7	65.5	-2.2	-1.0	-2.9	0.8
11	-222.7	-33.4	6.1	-2.8	-5.0	-1.0	21.4	110.2	4.5	-3.5	-5.7	-1.3
12	-376.5	-64.3	0.9	-4.8	-9.8	-0.6	35.6	216.0	1.2	-5.6	-10.8	-0.6
Historical[b]	13.2	76.7	-63.4	299.2	136.9	162.3	-157.3	-25.1	-132.2	156.9	77.8	79.1

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table C. Changes for each CALVIN groundwater basin inflow (%) (cont.)

	Source_GW-13			Source_GW-14			Source_GW-15			Source_GW-16		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.1	2.1	0.3	3.2	9.5	0.6	0.5	1.0	0.1	0.7	1.4	0.2
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	2.2	4.2	0.6	6.5	19.0	1.1	0.9	2.1	0.2	1.3	2.8	0.3
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	3.7	7.0	1.0	10.8	31.7	1.8	1.6	3.4	0.3	2.2	4.7	0.6
7	4.1	6.3	2.4	12.8	33.3	4.0	1.8	3.4	0.8	2.5	4.2	1.3
8	5.0	9.4	1.5	14.5	43.0	2.3	2.1	4.6	0.4	2.9	6.1	0.8
9	7.9	16.2	1.5	28.5	88.5	2.8	4.1	9.3	0.6	5.0	11.3	1.0
10	-0.4	-1.4	0.4	-2.7	-9.2	0.1	-0.4	-1.0	0.0	-0.3	-1.1	0.2
11	-1.6	-3.1	-0.5	-4.4	-11.4	-1.4	-0.7	-1.4	-0.2	-0.9	-1.9	-0.3
12	-2.7	-5.7	-0.4	-8.4	-24.8	-1.3	-1.2	-2.7	-0.2	-1.6	-3.6	-0.3
Historical[b]	872.1	380.7	491.4	314.6	94.3	220.2	1167.3	469.6	697.7	278.1	109.1	169.0

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table C. Changes for each CALVIN groundwater basin inflow (%) (cont.)

	Source_G-17			Source_GW-18			Source_GW-19			Source_GW-20		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.6	3.6	0.4	2.8	4.7	0.8	5.3	5.4	4.9	2.2	3.6	0.8
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	3.2	7.2	0.9	5.7	9.3	1.6	10.6	10.8	9.8	4.4	7.3	1.6
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	5.4	12.0	1.5	9.5	15.6	2.7	17.7	18.0	16.4	7.4	12.1	2.6
7	6.2	10.9	3.4	11.1	15.7	5.9	23.2	20.2	37.8	9.6	13.0	6.2
8	7.1	15.8	2.0	12.4	20.9	2.9	24.3	25.1	20.5	10.1	16.9	3.4
9	12.4	29.1	2.6	25.1	43.5	4.7	50.6	54.1	33.2	20.8	35.8	5.9
10	-0.6	-2.3	0.4	-2.0	-4.0	0.1	-5.6	-6.5	-1.3	-1.7	-3.5	0.0
11	-2.3	-4.9	-0.8	-4.2	-6.2	-2.0	-8.6	-7.7	-12.8	-3.5	-5.3	-1.6
12	-4.0	-8.9	-1.0	-7.2	-11.4	-2.4	-15.0	-14.4	-17.8	-6.1	-9.1	-3.1
Historical[b]	358.7	133.4	225.4	484.8	255.7	229.1	166.9	138.5	28.4	219.4	109.2	110.2

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Table C. Changes for each CALVIN groundwater basin inflow (%) (cont.)

	Source_GW-21		
Scenario[a]	**Annual**	**Oct.-Mar.**	**Apr.-Sep.**
1	0.0	0.0	0.0
2	2.9	4.4	1.2
3	0.0	0.0	0.0
4	5.9	8.8	2.3
5	0.0	0.0	0.0
6	9.8	14.6	3.8
7	12.4	15.7	8.3
8	13.3	20.5	4.2
9	28.5	45.0	8.0
10	-3.2	-5.2	-0.6
11	-5.3	-7.2	-2.9
12	-8.7	-11.6	-5.0
Historical[b]	390.4	216.8	173.6

a. 12 climate change scenarios described on page A-5.
b. Historical average in TAF.

Appendix VII — Attachment B

California Urban Water Demands for 2100

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Contents

Figures

Tables

B.1 Introduction

The CALVIN urban economic value preprocessor model (see Appendix B, Jenkins et al., 2001) has been used to develop urban water demand functions across California to drive the optimization by the CALVIN model. These value functions are developed from current and projected estimates of population, per capita water use, sector water use breakdowns (residential, commercial/public, and industrial), industrial water production values, and monthly use patterns for each urban area, as well as from estimates of the seasonal residential price elasticities of demand and current retail water price for each urban area represented in CALVIN.

Population estimates are based on a spatially disaggregated projection of population for the year 2100 (Landis and Reilly, 2002). These spatial data, at county and California Department of Water Resources (DWR) detailed analysis units (DAU) scales, have been aggregated into the different CALVIN urban nodes.

Per capita water use has been estimated using a California DWR 2020 projection of per capita urban water use as a baseline (DWR, 1998a). The change in population density has been translated into a change in per capita water use (pcu) using linear regressions of cross-sectional data on observed population density and pcu for distinct climatic regions in California.

Projections of land use conversion from agriculture to urban and likely location of new housing developments allow urban projections to be consistent with agricultural land use assumptions.

After analyzing the new urban demand projections, new economic urban water demand areas have been added to the CALVIN network, mainly in the Central Valley and in some parts of southern California.

B.2 2100 Projections of California's Urban Demands

The projected population and spatial distribution of urbanized land are taken from Landis and Reilly's study (2002) on California's urban population and footprint projections through the year 2100.

In this study, we project the annual county-level population growth through 2100. A cross-sectional regression model relating county infill shares to remaining "greenfield" land is then used to project future infill and greenfield shares. Projected greenfield population growth is allocated to undeveloped sites in each region in order of development probability. These probabilities are taken from four regional spatial/statistical growth pattern models calibrated to historical development, and estimated for individual 1 ha sites. The four regional models cover the lower Sacramento Valley, the San Joaquin Valley, the Bay Area and Central Coast, and southern California. Using a geographic information system (GIS) allows representation of these spatial patterns of growth in new urban areas, which is aggregated at the DAU and county level.

As a result of Landis and Reilly's study, projected population and urban land are available at the DAU level in 2100 for a "high" and "low" scenario. By further aggregation of DAU data, we obtain 2100 population and urban area for each CALVIN urban node. Figure B.1 compares the 2020 DWR population projections (currently used for estimating urban water demands in CALVIN for 2020) and the new 2100 "high" scenario projection. The largest percent increases in population, Table B.1, take place in Mojave, Coachella, Blythe and El Centro in Southern California, and in several urban nodes within the Central Valley [Central Valley Production Model (CVPM) 4, 8, 13, 17, 20].

B.3 Urban Water Demands Representation in CALVIN

The representation of California's urban water demands in CALVIN can be categorized in three groups according to their size and the way in which their water supply sources are modeled (see Appendix B, Jenkins et al., 2001, for a detailed explanation of the three categories):

1. Demands excluded from CALVIN analysis. These demands are supplied by sources outside the intertied water system modeled in CALVIN.

2. Demands included in CALVIN as fixed diversions (type "TS," for time series). Usually these are small demands represented as a fixed time series of deliveries.

3. Demands included in CALVIN as economic value functions. The model uses two approaches to represent these economic functions. The first approach combines all urban water use sectors and develops a single economic value function (type "CF," or combined demand function). The second approach separates industrial water use from residential and other water uses and develops two separate value functions (type "SF," or split demand function). See Appendix B, Jenkins et al., 2001, for a detail description of the methods, assumptions, and data used to develop the economic value functions.

For this 2100 study, the third category includes not only the original 19 urban demand areas economically represented in CALVIN for 2020 but also 11 additional areas. These 11 areas have been added to this category because of their expected high growth in water demand for year 2100.

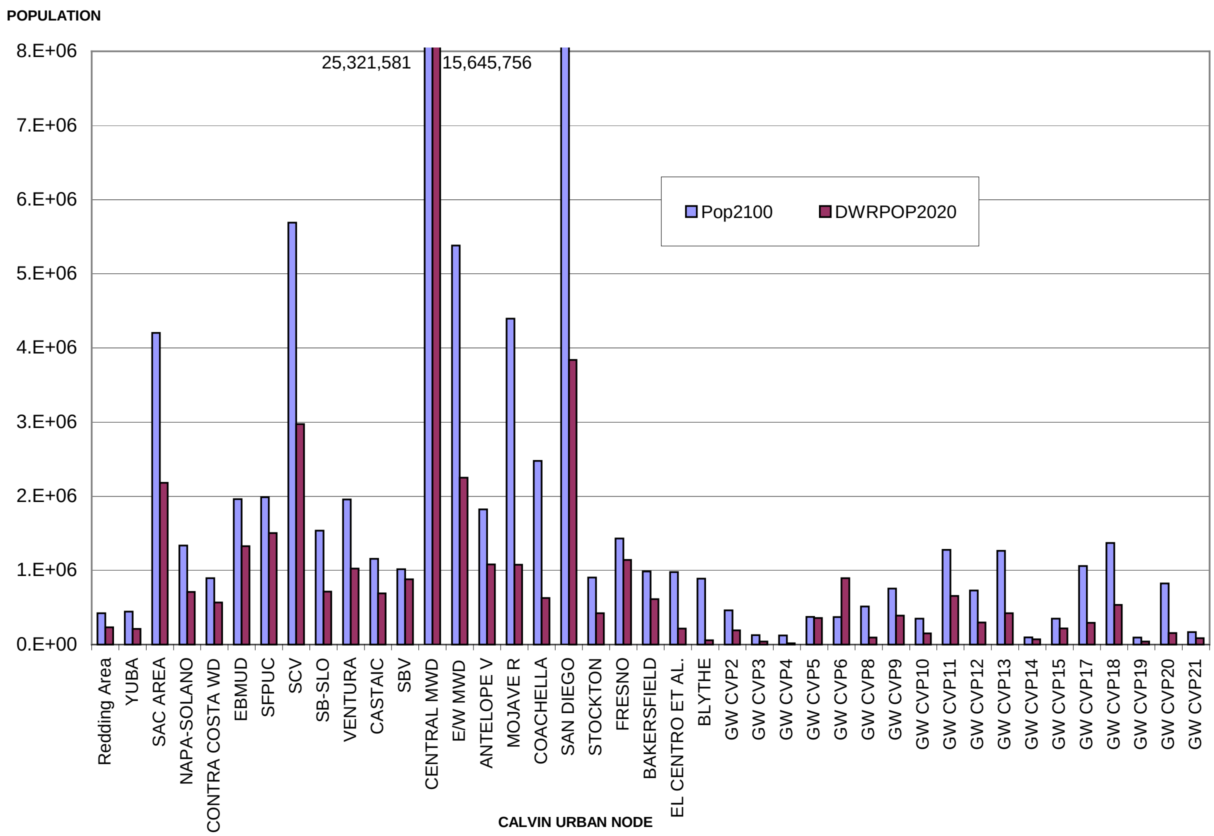

Figure B.1. 2020 DWR and 2100 population projections

Table B.1. Percent population increase from DWR 2020 projection to 2100 projection

Urban name	DWR 2020 population	2100 population	% population increment
Redding area	231,495	421,786	82
Yuba and others	210,450	442,266	110
Sacramento area	2,181,605	4,201,943	93
Napa-Solano	711,324	1,334,834	88
Contra Costa	565,353	896,486	59
East Bay Municipal Utility District (EBMUD)	1,326,460	1,961,825	48
San Francisco Public Utilities Commission (SFPUC)	1,501,900	1,987,120	32
Santa Clara Valley (SCV)	2,971,513	5,690,081	91
Santa Barbara–San Luis Obispo (SB-SLO)	713,675	1,534,167	115
Ventura	1,022,850	1,956,007	91

Table B.1. Percent population increase from DWR 2020 projection to 2100 projection (cont.).

Urban name	DWR 2020 population	2100 population	% population increment
Castaic	688,500	1,156,443	68
San Bernardino Valley Water District (SBV)	878,944	1,016,582	16
Central MWD	15,645,756	25,321,581	62
East/West MWD	2,251,030	5,381,640	139
Antelope Valley	1,079,650	1,821,155	69
Mojave River	1,075,775	4,395,538	309
Coachella	628,820	2,477,594	294
San Diego	3,839,800	8,078,707	110
Stockton	421,575	904,601	115
Fresno	1,142,125	1,429,670	25
Bakersfield	612,100	987,108	61
El Centro and others	214,250	977,078	356
Blythe	58,800	889,500	1,413
CVPM 2	190,110	461,137	143
CVPM 3	42,275	125,008	196
CVPM 4	17,565	121,927	594
CVPM 5	358,800	371,47[a]	4
CVPM 6	894,299	368,680[a]	-59
CVPM 8	92,445	514,633	457
CVPM 9	391,700	753,932	92
CVPM 10	150,580	350,271	133
CVPM 11	653,980	1,277,364	95
CVPM 12	297,770	727,016	144
CVPM 13	422,150	1,263,670	199
CVPM 14	69,375	97,531	41
CVPM 15	216,200	349,507	62
CVPM 17	294,210	1,060,199	260
CVPM 18	534,140	1,369,290	156
CVPM 19	41,100	95,210	132
CVPM 20	156,675	823,226	425
CVPM 21	84,150	166,539	98
Subtotal	44,881,273	85,560,323	91
Total California	47,507,399	92,081,030	94

a. Changed with regard to CALVIN 2020 model (DAU originally shared with Yuba and Napa-Solano are transferred fully from CVPM 5 and CVPM 6 demands to Yuba and Napa-Solano, respectively).

Per capita water use projections

Per capita water use has been estimated using the DWR 2020 projection of pcu by county as a baseline (DWR, 1998a, 1998b). That work assumed that urban water conservation options (BMPs, or best management practices) would be put into effect by 2020. The differences between the DWR 1995 baseline pcu (DWR 1998a, 1998b), previously used in CALVIN, and the 2020 base levels reflects the influence of the saving assumptions for BMPs, socioeconomic change, and differential population growth on pcu in each region, according to DWR projections.

In this work, the 2020 pcu baseline has been adjusted for 2100 to consider the population density effect on pcu. The change in population density from 2020 to 2100 has been translated into a change in pcu by using linear regressions between observed population density and current pcu. Two regression equations have been calibrated: one for inland DAUs and the other for coastal DAUs (Figures B.2 and B.3). As noted in these figures, the population density effect is higher for inland DAUs; climatic differences are expected to result in higher outdoor water use in inland areas (higher landscape irrigation requirements, sometimes as much as 60% of annual residential water use) compared with coastal regions in California. This would make inland pcu more sensitive to changes in population density, because higher density implies a smaller landscaped area per person. Figure B.4 displays the per capita water use for the different CALVIN urban nodes, obtained from the 2100 population (high scenario)-weighted average densities at the DAU level, under different pcu assumptions — the 1995 DWR pcus, the 2020 DWR pcus, and the regression-adjusted pcus, which are the values finally adopted for this study.

Other important factors affecting pcu are income effect, evolution of economic activities, and water pricing (for a discussion on the influence of these factors, see, for example, Baumann et al. 1998). Because it is difficult to make any type of extrapolation of these factors to the year 2100, we have found it more realistic to consider only the density effect over the 2020 pcu baseline.

B.4 Method for Generating 2100 Urban Penalty Functions

Urban monthly residential demand functions are generated from the available data and converted into penalty functions to drive the optimization model. The main steps in the generation of urban value functions are

1. Determination of year 2100 urbanized area and population at the DAU scale from Landis and Reilly’s (2002) urbanized spatial footprint projections and population growth forecasts.

2. Grouping and mapping of DAUs into CALVIN urban nodes.

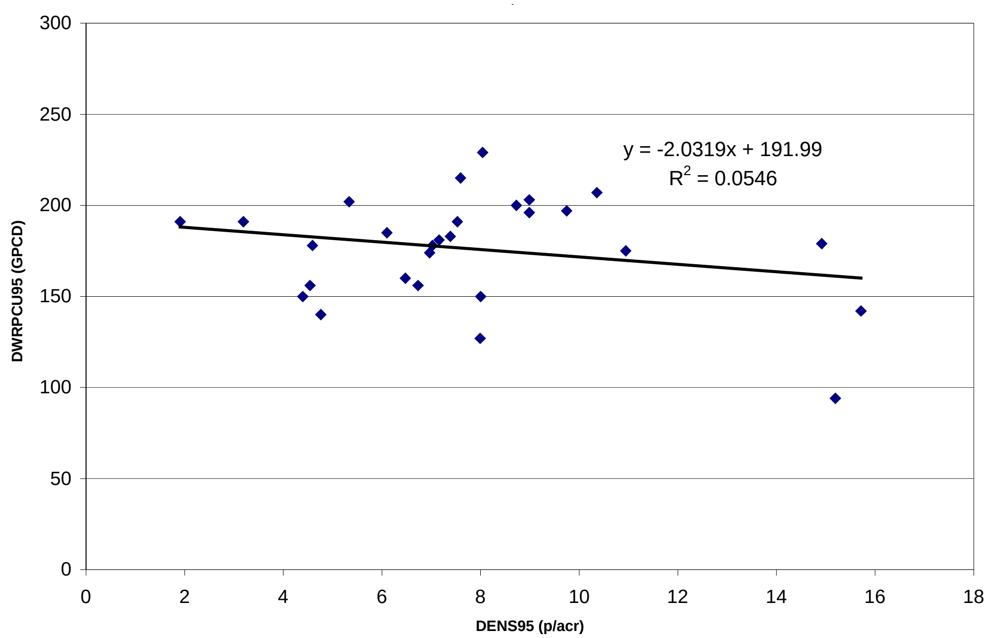

Figure B.2. PCU versus population density regression for DAUs in coastal areas

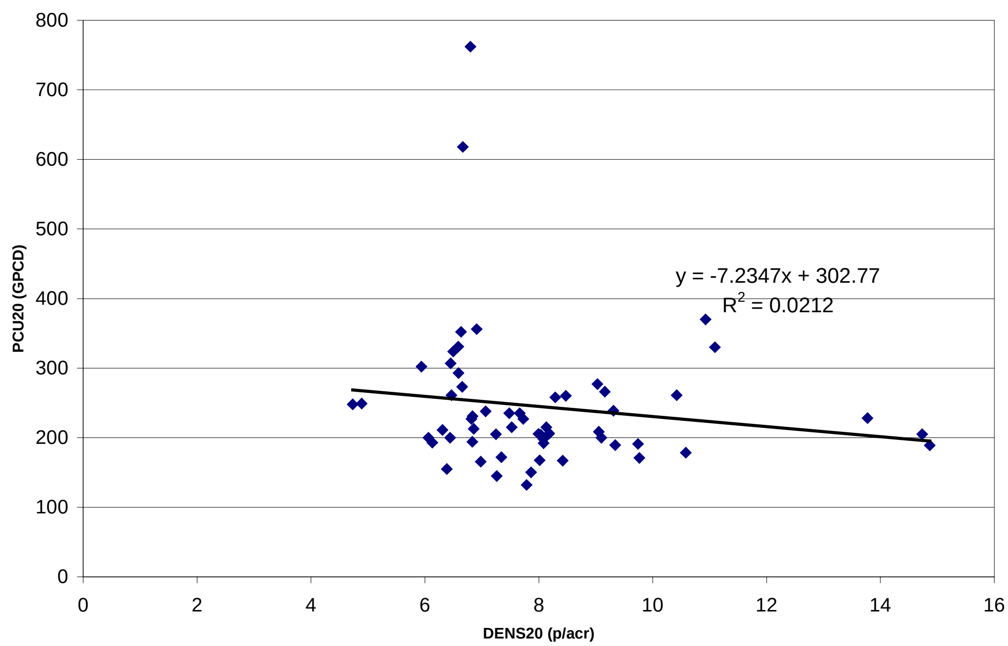

Figure B.3. PCU versus population density regression for DAUs in inland areas

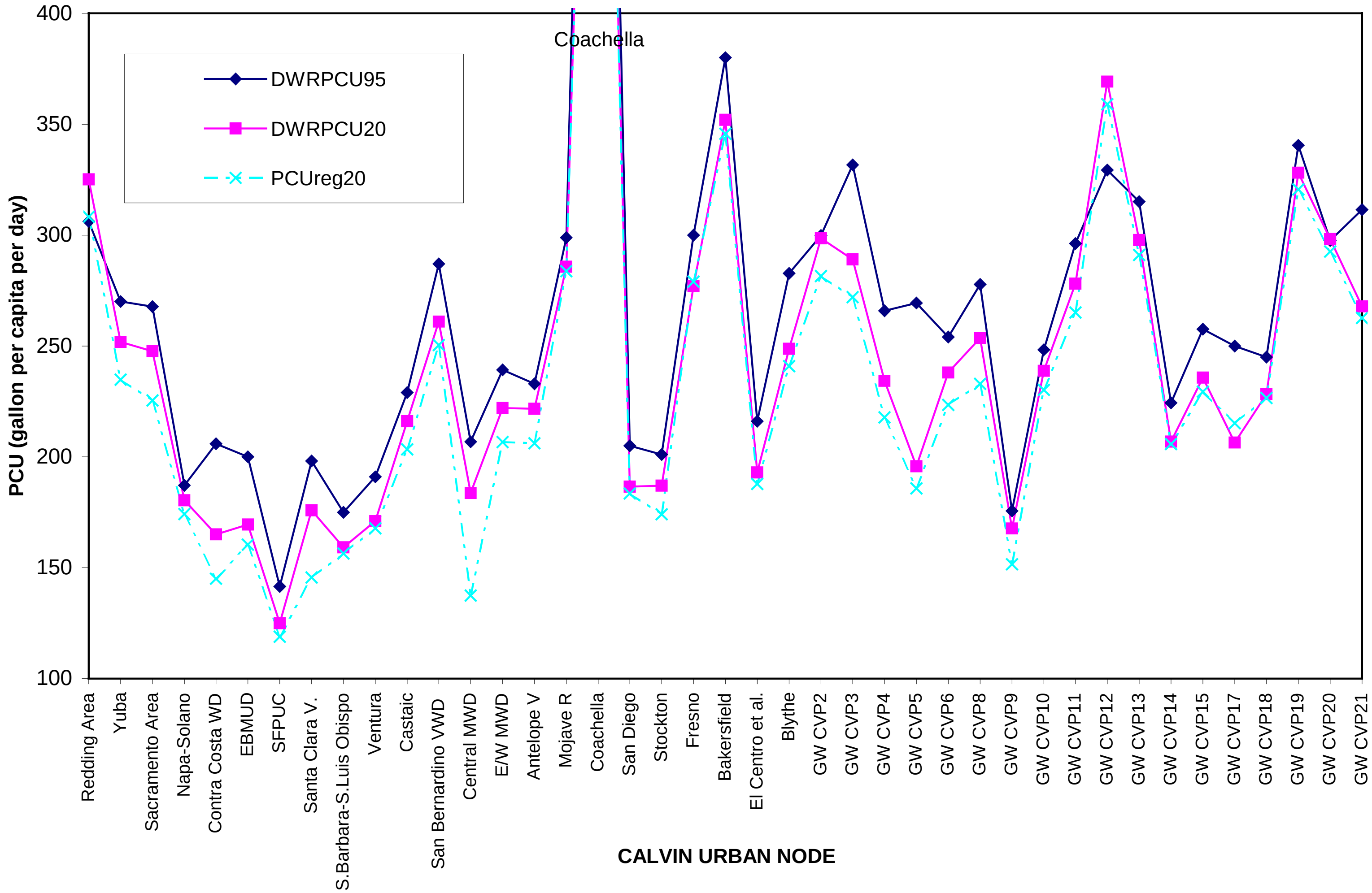

Figure B.4. Per capita water use comparison

3. Projection of 2100 populations and urbanized land for DAUs outside Landis and Reilly's spatial footprint projection boundaries using the county-level population and urbanized land growth estimates. This approach has been applied to DAUs corresponding to CALVIN's economically represented urban nodes of Redding (DAUs 141 and 143) and Yuba (to DAU 167), and to DAUs in several other Central Valley urban demand areas in CALVIN (CVPM2, CVPM4, CVPM 5, and CVPM8).

4. Aggregation of the DAU's projected population and per capita water use data into CALVIN urban nodes. Per capita water use in each CALVIN node is obtained from the population-weighted average of the pcu of the DAUs composing that node.

5. Correction of data for DAUs that are split across CALVIN nodes.

6. Calculation of the annual water demand based on population and pcu.

7. Breakdown of demands by months and sectors. The demands are split into three sectors (residential, industrial, and others) according to statewide information available from DWR (1993). For each urban area, annual demand is disaggregated into monthly demands according to a monthly use pattern, derived from 1980-1990 statewide agency monthly municipal and industrial production data published in Bulletin 166-4 (DWR, 1994). In urban demand areas with separate industrial value functions, an industrial average monthly use pattern (California Urban Water Agencies [CUWA], 1991) is applied to the industrial portion of the demand.

8. Using 1995 observed retail water prices and estimated seasonal price elasticity of water demand, the monthly penalty functions on water deliveries for each demand were generated for projected conditions. Prices for urban water are based on the 1995 California survey of residential water prices (Black and Veatch, 1995). Different long-term elasticity values are considered for winter, summer, and intermediate months (see references in Appendix B, Jenkins et al., 2001). No attempt has been made to adjust residential prices, elasticities or sector breakdown, and monthly use patterns from 2020 to 2100.

The penalty for any delivery less than the maximum demand equals the forgone benefit caused by water scarcity, equivalent to the area (integral) under the demand curve from the maximum demand (maximum = projected population times projected pcu) left-ward to the water delivery level. Commercial and governmental demands are assumed to be price insensitive. Therefore, the commercial and governmental target demand is added to the residential water delivery level to shift the penalty function to the right for each urban demand. The penalty function for industrial

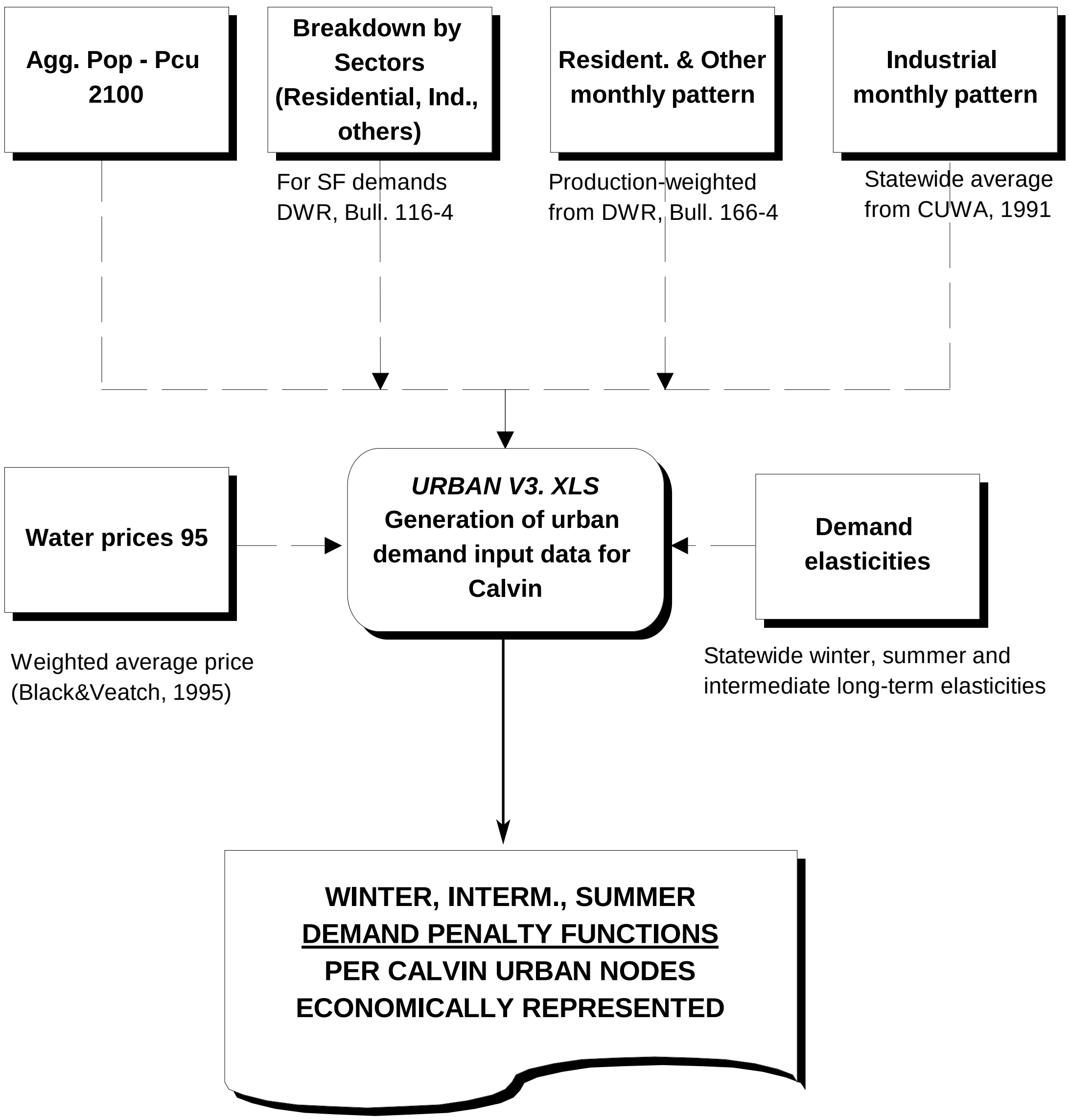

Figure B.5. Generation of urban water value functions for CALVIN

water demand is represented as a simple linear function of water shortages, using data for production losses for a 30% cutback in 1991 (CUWA, 1991). Figure B.5 summarizes the information that the processor uses to generate the urban water penalty functions.

B.5 California's Urban Water Demands for 2100 "High" Scenario

To compute 2100 urban water demand for each DAU, the adjusted 2100 pcu was multiplied by the 2100 population forecast. The DAU results have been aggregated at the CALVIN urban node level and a set of monthly penalty functions has been generated for each of the urban demands, following the steps described in the last section.

After analyzing the 2100 results, 11 more economically represented urban demands (that were represented previously as fixed diversions) have been added to the 19 original ones at the 2020 level of development, based on expected growth in water demand and the likely need for new water supplies to meet high growth. Figure B.6 displays the projected 2100 "high" water demand for each CALVIN urban node compared to the 2020 urban water demands previously used in CALVIN (see Appendix B, Jenkins et al., 2001).

Tables B.2 and B.3 list the existing and new economically represented urban demand areas in CALVIN, respectively. Table B.4 provides the DAU-level data for the urban demands newly represented with economic value functions for 2100. Table B.5 lists the demands that remain as fixed diversions (all are small demands in the Central Valley), their aggregated DAUs, and their 2020 and 2100 urban water demand. Finally, Figure B.6 displays the previous CALVIN urban water demands (year 2020 projection) and the final 2100 urban water demands for each urban CALVIN demand area.

For the three Metropolitan Water District (MWD) areas modeled in CALVIN (Central MWD, East and West MWD, and San Diego), the representation of the demands in the 2020 CALVIN model have been changed from the hydrologically varying representation used over the 72 year period (from October 1921 to September 1993) to average year representation for 2100 urban demands. The monthly use patterns for an average year are obtained from the historical average monthly pattern provided by MWD.

CALVIN urban demands for Antelope, Castaic Lake, Napa-Solano, Yuba, and Redding, which were previously represented as net demands in the CALVIN 2020 model (local supplies not modeled in CALVIN were deducted from these full target demand; see Appendix B, Jenkins et al., 2001), are now represented by their total target demand. These local supplies are explicitly represented as a fixed inflow time series.

A new demand has been created, Blythe, made up of Colorado River Hydrologic Region Planning Sub-Areas 02 and 03 (CR2 + CR3), given the high expected population growth in this area bordering the Colorado River. Likewise, Colorado Hydrologic Region Planning Sub-Area 05 (CR5) has been added to the original CALVIN 2020 San Diego urban node (DAU 120) for the year 2100.

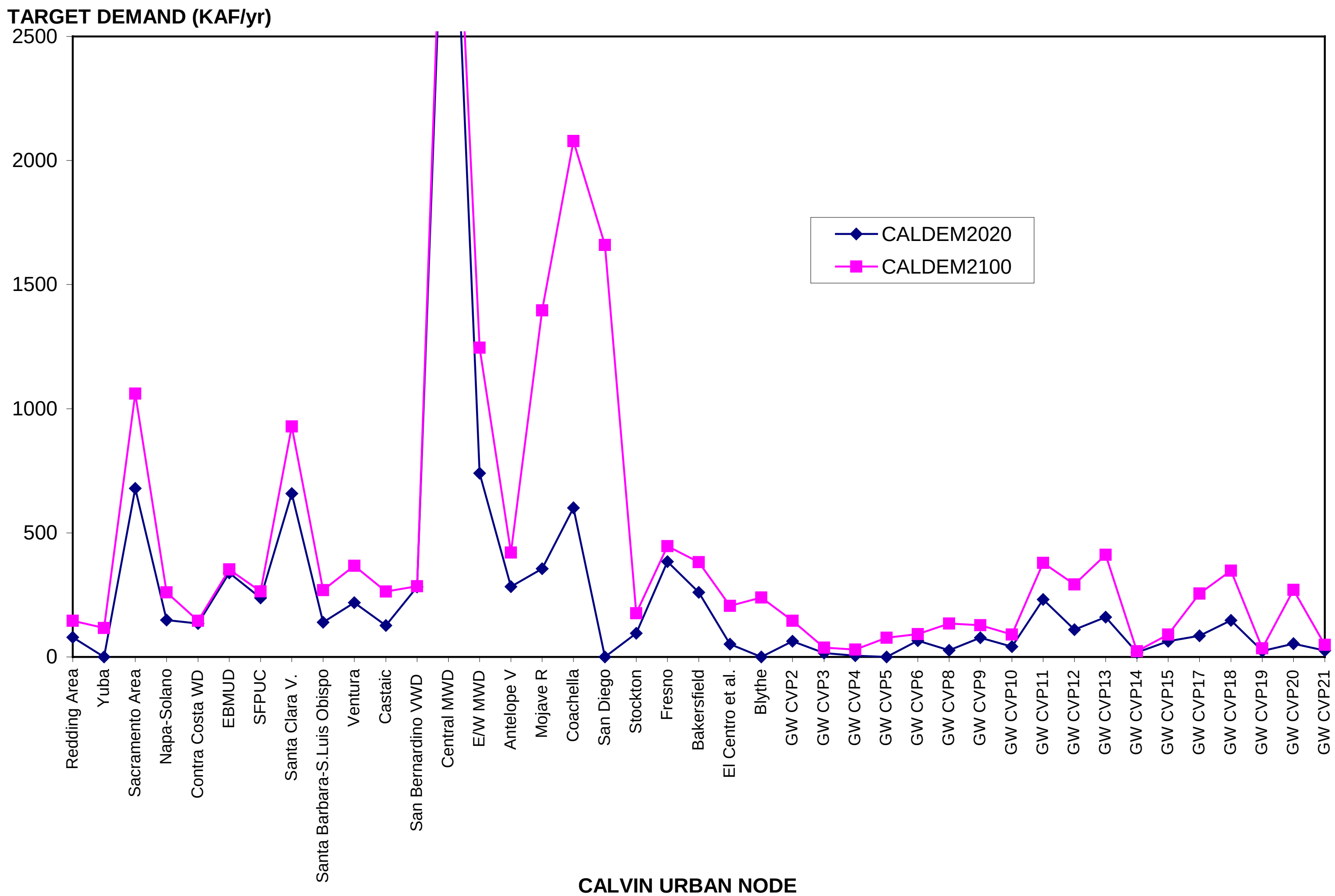

Figure B.6. CALVIN 2020 and 2100 urban water demands

Table B.2. Existing economically represented urban demand areas in CALVIN

#	CALVIN node name	DAUs included	2020 demand TAF/year	2100 demand TAF/year	Description of major cities, agencies, or associations
20	Yuba City and others	159, 168	63.83	116.33	Oroville, Yuba City
30	Sacramento Area	172, 173, 158, 161, 186	678.51	1,061	Sacramento Water Forum, Isleton, Rio Vista, PCWA, EID, W. Sacramento, N. Auburn
50	Napa-Solano	191, 40, 41	148.8	260.50	Cities of Napa and Solano Counties
60	Contra Costa WD	192, 70% of 46	134.80	145.60	Contra Costa Water District
70	EBMUD	70% of 47, 30% of 46	297.30	352.30	East Bay Municipal Utility District
80	SFPUC	43	238.01	264.50	San Francisco PUC City and County and San Mateo County service areas not in node 90
90	SCV	44, 45, 62, 30% of 47	657.70	927.90	Santa Clara Valley, Alameda County and Alameda Zone 7 WD
110	Santa Barbara-San Luis Obispo	67, 68, 71, 74, 75	139.20	268.70	Central Coast Water Authority
130	Castaic Lake	83	176.58	263.40	Castaic Lake Water Agency
140	SBV	44% of 100	282.52	285.10	San Bernardino Valley Water District
150	Central MWD	87, 89, 90, 92, 96, 114, 56% of 100	3,730.70	3,898.8	Mainly Los Angeles and Orange County portions of Metropolitan Water District of Southern California (MWD)
170	Eastern and Western MWD	98, 104, 110	740.04	1,245.7	Mainly Riverside County portion of MWD
190	Antelope Valley Area	SL3, SL4	283.30	420.4	AVEKWA, Palmdale, Littlerock Creek
200	Mojave River	SL5, CR1	354.90	1,396.97	Mojave Water Agency and Hi Desert Water Agency
210	Coachella Valley	CR4 (348, 349)	600.73	2,078.54	Dessert Water Agency, Coachella Valley Water Agency
230	San Diego MWD[a]	120 + CR5	988.12	1,660.04	All of San Diego County
240	Stockton	182	94.90	176.40	City of Stockton
250	Fresno	233	383.74	446.80	Cities of Fresno and Clovis
260	Bakersfield	254	260.50	382.20	City of Bakersfield
	Total		10,254	15,535	

a. Area expanded from 2020 CALVIN representation to include CR5.

Table B.3. New 2100 economically represented urban demand areas in CALVIN

#	CALVIN node name	DAUs included	2020 demand TAF/year	2100 demand TAF/year	Description of major cities, agencies, or associations
10	Redding	141, 143	79.4	145.6	Redding
120	Ventura	81	218.8	367.5	Oxnard (Camarillo, Ventura)
270	El Centro and others	all CR6	51.8	205.5	El Centro, Calexico, Brawley
280	Blythe and others[a]	CR2, CR3	-	239.9	Blythe, Needles
308	CVPM 8 Urban	180, 181, 184	26.4	134.3	Galt
311	CVPM 11 Urban	205, 206, 207	231.7	379.19	Modesto, Manteca
312	CVPM 12 Urban	208, 209	109.6	292.3	Turlock, Ceres
313	CVPM 13 Urban	210-215	160.8	411.9	Merced, Madera
317	CVPM 17 Urban	236, 239, 240	85.0	255.5	Sanger, Selma, Reedley, Dinuba
318	CVPM 18 Urban	242, 243	147.1	347.4	Visalia, Tulare
320	CVPM 20 Urban	256, 257	53.9	269.7	Delano, Wasco
	Total		1,164.5	3,048.8	

a. Excluded urban demand in 2020 CALVIN model.

Table B.6 shows the total population and urban water demand values from the previous 2020 CALVIN study and from the 2100 projection.

B.6 Limitations

A number of limitations are contained in the 2100 urban water value functions estimated here for use in CALVIN. Most result from the difficulty in predicting changes in water use characteristics, patterns, and costs and values that could occur in the state by 2100. The most apparent limitations include:

1. CALVIN water demands functions for 2100 are developed assuming current seasonal estimates of the price elasticity of demand and the current retail water price; no adjustment is made for possible changes in either the price elasticity or the water prices.

2. No further BMPs in urban water conservation beyond those expected to be in place by 2020 (projections in DWR, 1998a) are added for 2100.

3. Bulk pcu projections for 2100 from 2020 estimates consider only the effect of increased population density on outdoor water use and ignore income effects that might occur as well as possible changes in the level of industrial, commercial, and public water use in different parts of the state.

Table B.4. Data for demands with added economic function

CALVIN node no.	CALVIN node name	DAUs	Population 1997	Population 2100	Change in population 1998-2100	Main growth center (city)	Current supply[a]	Increase in urban land 2020-2100 (ha)	Reduction in agricultural land 2020-2100 (ha)	Reduction in agricultural water (TAF/year)	Possible new sources
10	Redding[a]	141	62,775	146,581	83,806	Redding	70% SW, 30% GW	Not available	-	-	
10	Redding	143	83,930	275,205	191,275	Redding		Not available	-	-	
120	Ventura	81	716,176	1,956,007	1,239,830	Oxnard (Camarillo, Ventura)	71% SW, 21% GW	34,272	-	-	
270	El Centro	CR6	139,332	977,078	837,746	El Centro, Calexico, Brawley	100% SW	38,733	-	-	
280	Blythe	CR2	198	307,704	307,506	Blythe		16,246	-	-	
280	Blythe	CR3	29,677	611,671	581,994			24,255	-	-	
308	Urban CVPM 8	180	37,102	485,388	448,286	Galt	100% GW	7,504	-	194	
308	Urban CVPM 8	181	10,850	28,741	17,891			Not available	-		
308	Urban CVPM 8	184	361	504	143			0	-		
311	Urban CVPM 11	205	94,511	528,849	434,338	Manteca	100% GW	13,498	21,173	180	
311	Urban CVPM 11	206	229,925	743,501	513,576	Modesto	100% GW	11,119			
311	Urban CVPM 11	207	2,721	5,014	2,293			6			
312	Urban CVPM 12	208	203,822	723,559	519,737	Turlock, Ceres	100% GW	12,731	11,131	86	
312	Urban CVPM 12	209	2,257	3,457	1,200			0			
313	Urban CVPM 13	210	130,333	557,475	427,142	Merced	100% GW	16,671	34,671	270	
313	Urban CVPM 13	211	6,584	20,705	14,121			695			
313	Urban CVPM 13	212	5,542	110,506	104,964			5,122			

Table B.4. Data for demands with added economic function (cont.)

CALVIN node no.	CALVIN node name	DAUs	Population 1997	Population 2100	Change in population 1998-2100	Main growth center (city)	Current supply[a]	Increase in urban land 2020-2100 (ha)	Reduction in agricultural land 2020-2100 (ha)	Reduction in agricultural water (TAF/year)	Possible new sources
313	GW CVP13	213	48,647	415,809	367,162	Madera	50% SW, 50% GW	15,039	34,671	270	
313	GW CVP13	214	21,158	147,074	125,916			5,212			
313	GW CVP13	215	1,496	12,101	10,605			391			
317	GW CVP17	236	88,580	784,570	695,989	Sanger, Selma	100% GW	33,705	37,443	270	
317	GW CVP17	239	53,991	259,800	205,809	Reedley, Dinuba	100% GW	10,268			
317	GW CVP17	240	9,165	15,829	6,664			128			
318	GW CVP18	242	222,435	913,651	691,216	Viaslia, Tulare	100% GW	27,905	3,076	24	
318	GW CVP18	243	100,536	455,639	355,103			15,512			
320	GW CVP20	256	70,973	617,378	546,405	Delano, Wasco	100% GW	25,701	24,012	177	
320	GW CVP20	257	11,270	205,848	194,578			6,579			

a. SW = surface water supply; GW = ground water supply.

Table B.5. Fixed diversion urban demand areas in CALVIN

CALVIN node name	DAUs	2020 demand TAF/year	21000 demand TAF/year
Urban CVPM 2	142, 144	63.8	145.42
Urban CVPM 3	163	15.7	38.09
Urban CVPM 4	164, 165, 167	5.24	29.75
Urban CVPM 5	166, 170, 171[a]	112.1	77.33
Urban CVPM 6	162[a]	200.9	92.28
Urban CVPM 9	185	77.1	127.97
Urban CVPM 10	216	41.9	90.28
Urban CVPM 14	244, 245	17.4	22.48
Urban CVPM 15	235, 241, 246, 237-8	63.3	89.80
Urban CVPM 19	255, 259, 260	23.4	34.18
Urban CVPM 21	258, 261	25.8	48.99
Total		646.6	796.6

a. Changed with regard to CALVIN 2020 model (DAU originally shared with Yuba and Napa-Solano are transferred fully from CVPM 5 and CVPM 6 demands to Yuba and Napa-Solano, respectively).

Table B.6. Total CALVIN 2020 and 2100 population and urban water demands

	2020 projection	2100 projection	% increase
Population CALVIN	44,881,273	85,560,323	91
Population California	47,507,399	92,081,030	94
CALVIN urban water demand (MAF/yr)	12.061	19.380	61

4. The monthly pattern and amount of outdoor landscape water use in each urban demand area across the state in 2100 ignores the effects of climate change, holding these at the same values used in 2020.

5. The 2020 CALVIN scaled values for industrial water shortages at the county level (taken from 1991 surveys) are used unchanged in 2100. These values are given as dollar of production lost per fractional cutback in water availability from desired levels. Other estimates would require predicted changes in the level and type of industrial activity as well as changes in industrial water use practices by 2100.

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Appendix VII – Attachment C

Hydropower in the CALVIN Model

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Contents

Figures

Tables

Abstract

California water system operators use hydropower extensively to capture and manage energy and provide economic returns to system operation. This attachment outlines efforts to include economic values for hydropower in the latest version of CALVIN, a large-scale optimization model of California's intertied system. The methods for efficiently representing the nonlinearity of hydropower in CALVIN's network flow algorithm are presented, along with initial test results, data documentation, and suggested improvements.

C.1 CALVIN Hydropower

C.1.1 Hydropower in California

California's water system is physically and institutionally complex. System entities operate the extensive network of reservoirs, rivers, canals, and diversions, as well as pumping and power plants with varying levels of coordination to meet a wide array of urban, agricultural, and environmental needs. Operational criteria for this system include water supply quantity and quality for urban and agricultural demands, flood control, minimum instream flow requirements, wetland requirements, and hydropower. Because most facilities were developed primarily for water supply and flood control, hydropower typically serves a lesser purpose in system operations. Although often institutionally subordinate, hydropower nonetheless provides large economic returns to facility operations, and is thus an important criterion to consider when assessing economically driven management alternatives.

The California Energy Commission (CEC) lists 386 licensed hydropower facilities in the state, ranging from the 1495-MW Castaic facility to local installations of less than 100 kW (CEC, 2001). In 1999, California produced 41,617 GWhr of hydropower, or approximately 15% of the power consumed by the state during that year (CEC, 2002). Such an extensive list reflects California's varied topography, because hydropower depends on one essential ingredient — falling water. Within the United States, only Washington State exceeds California's hydropower generation potential (U.S. Department of Energy [DOE], 2002), although only a fraction of this potential is being utilized. The elevation difference, or "head," needed to drive turbines can originate through natural or synthetic means. Most of the facilities that capitalize on naturally falling water capture runoff from mountainous areas and are located in the wetter northern region of the state and throughout the Sierra Nevada and Coast mountain ranges. Typically, greater heads and lower storage capacities characterize higher elevation facilities, and most of the larger storage facilities are located at lower elevations.

Some hydropower facilities are designed to use synthetic head created from pumped water. For example, energy used to pump State Water Project water over the north side of the Tehachapi Mountain range in Southern California is partially recovered on the southern side of the range through a series of hydroelectric facilities, offsetting the costs of delivering water to Southern California demands. Pumped storage facilities, such as San Luis Reservoir, are another major example.

Different operational criteria apply to various hydropower facilities, depending on their physical and institutional flexibility. Because wholesale electricity prices follow diurnal, seasonal, and annual cycles, operators of “peaking” plants seek to utilize a reservoir’s storage capacity by releasing water when wholesale electricity prices are highest, maximizing economic returns. Hydropower facilities with little or no storage or reservoirs, where downstream demands are the primary operational consideration (“base load” plants), may not have this flexibility, and must release water in nonpeak periods. Several storage facilities in California advantageously use an afterbay by pumping water from the afterbay into the reservoir in non-peak hours and releasing water from the reservoir in peak hours. This generates revenue through the electricity price differential.

The State Water Project (SWP) and the federal Central Valley Project (CVP) extensively augment their water supply systems with hydropower plants. Utility companies such Pacific Gas & Electric and Southern California Edison, as well as several municipal utility districts, operate hydropower facilities as an integral component in their power supply systems. In addition, irrigation districts may generate power for local consumption or for sale to the wholesale market.

C.1.2 Hydropower in CALVIN (Phase I)

CALVIN is an optimization model of California’s entire intertied water supply system and includes 90% of the urban and agricultural water demands in the state. This highly complex system is governed by physical capacities, connections, and constraints, as well as by an extensive array of agreements, contracts, and regulations. Because of the size and complexity of the system, a fairly simple modeling approach was needed — an approach that would characterize the system with sufficient accuracy, yet allow analysis to remain tractable. HEC-PRM, a network flow optimization package from the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), was chosen as CALVIN’s engine because of its flexibility and scalability. However, although a network flow algorithm (a simplified form of linear programming) greatly reduces computational requirements compared to other approaches, it also requires mathematical relationships between model elements to be linear. This linear stipulation required alternative methods of representing the nonlinearity of most hydropower facilities. The iterative method included in HEC-PRM (discussed later in this attachment), is computationally burdensome and ultimately rendered analysis of a large-scale system such as CALVIN intractable.

Because of these computational difficulties, only eight fixed-head facilities (easily represented linearly) were included in the first phase of CALVIN's development (Appendices G and H in Jenkins et al., 2001). In this attachment, we report our efforts to include variable-head hydropower in CALVIN in the second phase of model development. Characterization of all 386 plants was difficult because of time and data limitations, so facility selection criteria were used to narrow the list of facilities included.

C.1.3 Criteria for inclusion in CALVIN (Phase II)

Only plants with generating capacities greater than 30 MW were considered, with the exception of a few fixed-head facilities for which ample data were available. Parameters for several small powerplants on the California Aqueduct, for example, were easily obtained from DWRSIM (California Department of Water Resources [CDWR], 1996) and were therefore included.

In addition, only facilities within the boundaries of the first phase of CALVIN's development were modeled. CALVIN uses rim inflows from DWRSIM and several other planning models. Historical unimpaired hydrology and powerplant parameter data above these inflows are either unavailable or extremely difficult to reconstruct. Omission of these upstream facilities, however, is typically of little importance from the perspective of the management of California's intertied system. As discussed earlier, these upstream facilities are higher in elevation and are typically low-storage systems, making system operation relatively inflexible and reducing the potential for applying alternative management strategies. Implementing these two criteria reduced the list of facilities to be included in CALVIN from 386 to 32.

C.2 Hydropower Modeling Methodology

C.2.1 Hydropower equation

Equation C.1 is the instantaneous hydropower equation and shows that the economic benefit from hydropower at any point in time is a function of the price of electricity, the unit weight of water (62.4 lb/ft^3), the flow rate through the system, the head, the efficiency with which the turbine converts the water's energy to electrical power, and a unit conversion factor. Integrating this function over a given time period results in the total economic benefit over that period.

$$B_t = p_t c \gamma Q_t H(S_t) e \tag{C.1}$$

Figure C.1 illustrates how a reservoir storage system translates into these hydropower parameters. The head is considered to be the elevation difference between the surface of the reservoir and the tailwater below the power plant. It is this elevation difference that creates a "pressure" difference across the turbine. The elevation of the reservoir surface depends on the amount of water stored behind the dam, necessitating a relationship between storage and elevation that translates storage into head.

The conversion factor and the specific weight of water are considered constant. With a few exceptions, efficiency is also assumed to be fixed (although efficiency technically varies with flow rate and head, it remains fairly constant over a normal operating range).

Because CALVIN is a monthly timestep model, average monthly values for p_t, Q_t, and $H(S_t)$ are substituted into the equation. This requires the use of an average electricity price, entailing assumptions of how the facility will be operated (for peaking or base load management, for example). All facilities use an average monthly price in CALVIN (see Table C.1), regardless of their typical operation.

Reservoir

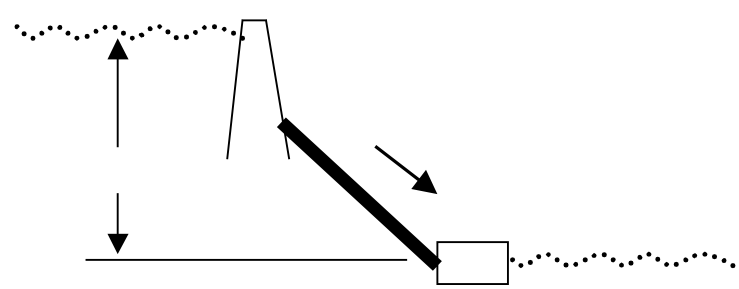


Figure C.1. Hydropower system

Table C.1. Wholesale electricity prices used in CALVIN (cents/kWh)

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2.0	2.0	2.0	1.8	1.8	1.8	3.0	3.0	3.0	2.6	2.6	2.6
URS (2002).											

Substituting these parameters into Equation C.1 results in the modified monthly benefit equation (Equation C.2) used in CALVIN (in the cases where efficiency is considered constant):

$$B_m = p_m c \gamma Q_m H(S_m) e \text{, for month } m \tag{C.2}$$

The nonlinearity of the hydropower function arises predominantly from $H(S_m)$. Power plants where storage head is a significant portion of the total head (known as variable-head facilities) exhibit highly nonlinear benefit functions. Conversely, in facilities with small storage head to total head ratios, benefits are roughly proportional to flow rate. $H(S_m)$ is constant for facilities with little or no storage capacity (fixed-head facilities), and the economic benefit becomes a linear function of flow rate.

C.2.2 Data sources

Parameters for hydropower facilities in the SWP and the CVP were gleaned from the hydropower postprocessor within DWRSIM. The postprocessor provided “power factors” for variable-head plants at various storage levels and “flow factors” for fixed-head plants. These factors combine several of the hydropower parameters into a single coefficient, which gives monthly estimates of energy generation when multiplied by the flow rate. These power and flow factors were easily assimilated in CALVIN, and 18 of the 32 plants represented in CALVIN use DWRSIM parameters.

Physical parameters were used to build individual representations of the remaining facilities. $H(S_m)$ functions were calculated using published storage and elevation data and estimated average tail water elevations. A default overall constant efficiency of 85% was assumed for facilities where efficiencies were unknown.

C.3 Four Methods for Representing Hydropower

HEC-PRM employs a cost-minimization algorithm, requiring that benefits be modeled as linear or convex piecewise linear penalty functions. These penalties are equivalent to the unrealized loss of benefit from *not* operating the system at maximum capacity; i.e., at maximum head (storage) and release (see Figure C.2 and Equation C.3). CALVIN balances these hydropower “penalties” with other costs in the system and suggests operations that minimize overall costs to the entire system.

$$P_m = B_{\max,m} - B_m \tag{C.3}$$

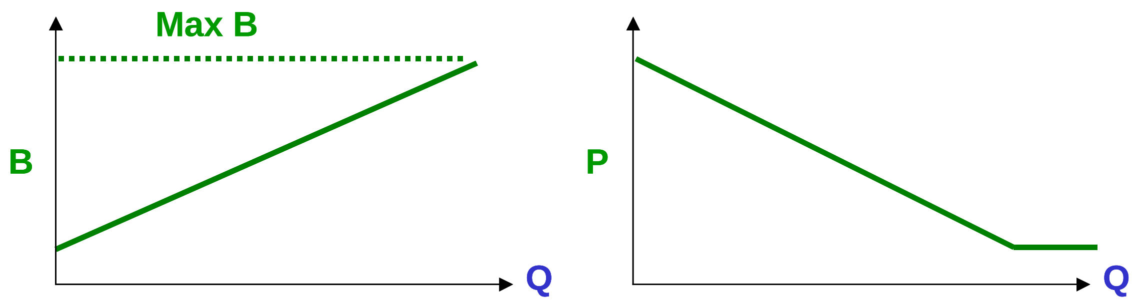


Figure C.2. Relationship between benefit and penalty function (at constant S and e)

Four different methods were used in generating hydropower penalty functions, based on facility configuration, data availability, and computational considerations. Two methods were used for fixed-head facilities, and two for variable-head plants with penalty functions expressing varying degrees of nonlinearity.

C.3.1 Unit cost on flow (UC): Fixed-head, constant efficiency

For fixed-head facilities with an assumed constant efficiency, penalty functions are a simple linear function (see example in Figure C.3). All facilities with unit costs on flow are based on DWRSIM power factors. The x-intercept represents the flow capacity of the plant.

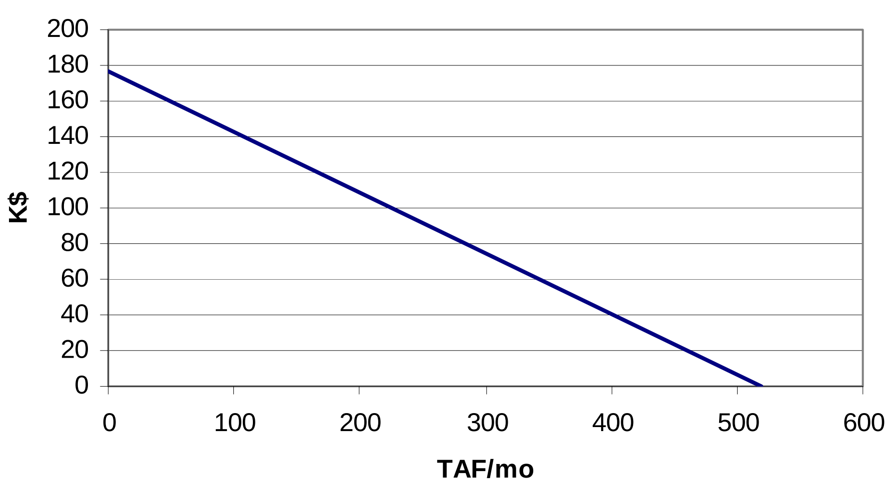


Figure C.3. Mojave Syphon penalty function (July)

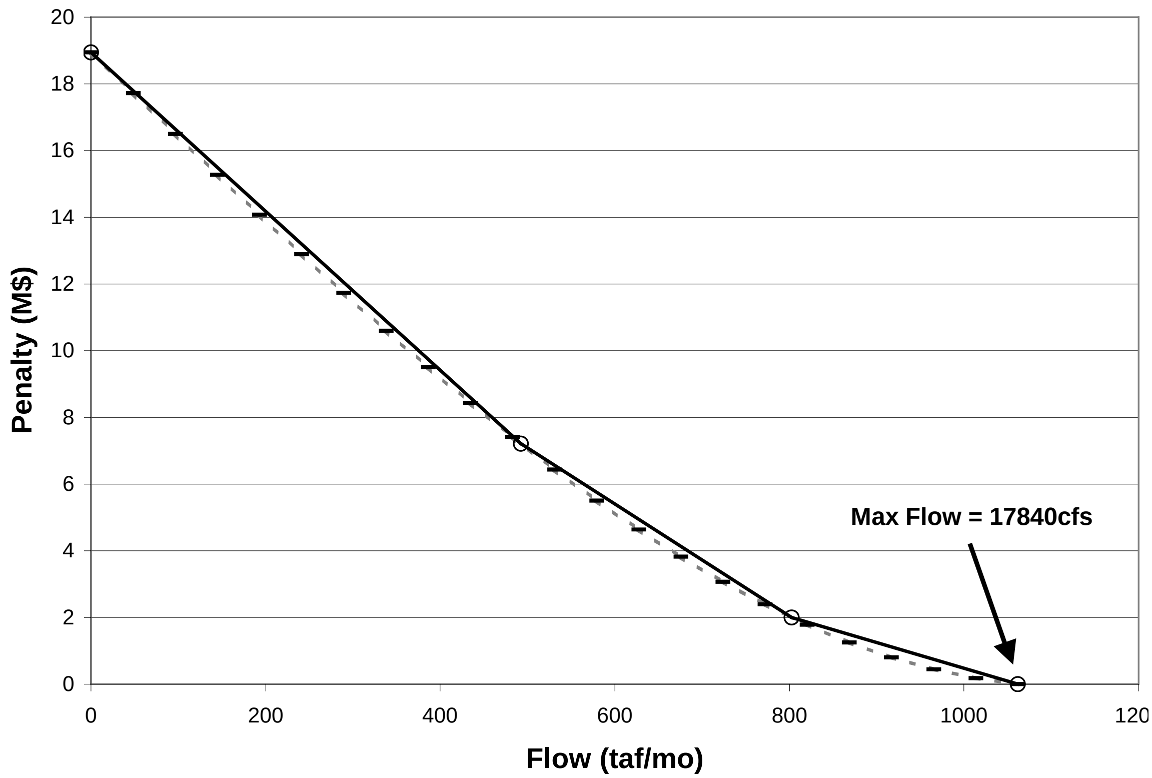


Figure C.4. Castaic Powerplant penalty function (July)

C.3.2 Piecewise linear cost on flow (PWL): Fixed head

DWRSIM lists several large nonstorage facilities where head is a function of flow because of head losses at varying flow rates. These plants exhibit a slightly nonlinear convex penalty function. To capture this nonlinearity, a least-squares approach was utilized to fit a three-piece linear approximation to the nonlinear function (see Figure C.4). A Visual Basic macro utilized the Solver function in Microsoft Excel to choose breakpoints along the nonlinear penalty that maximized the coefficient of determination of the piecewise linear fit. The only facilities modeled with this method were the Castaic and Warne power plants in Southern California.

Additionally, flow-power factor relationships were provided by DWRSIM for the Nimbus and Keswick power plants. These data sets were incorporated directly into piecewise linear penalties in CALVIN, and did not require the least-squares approximation described above.

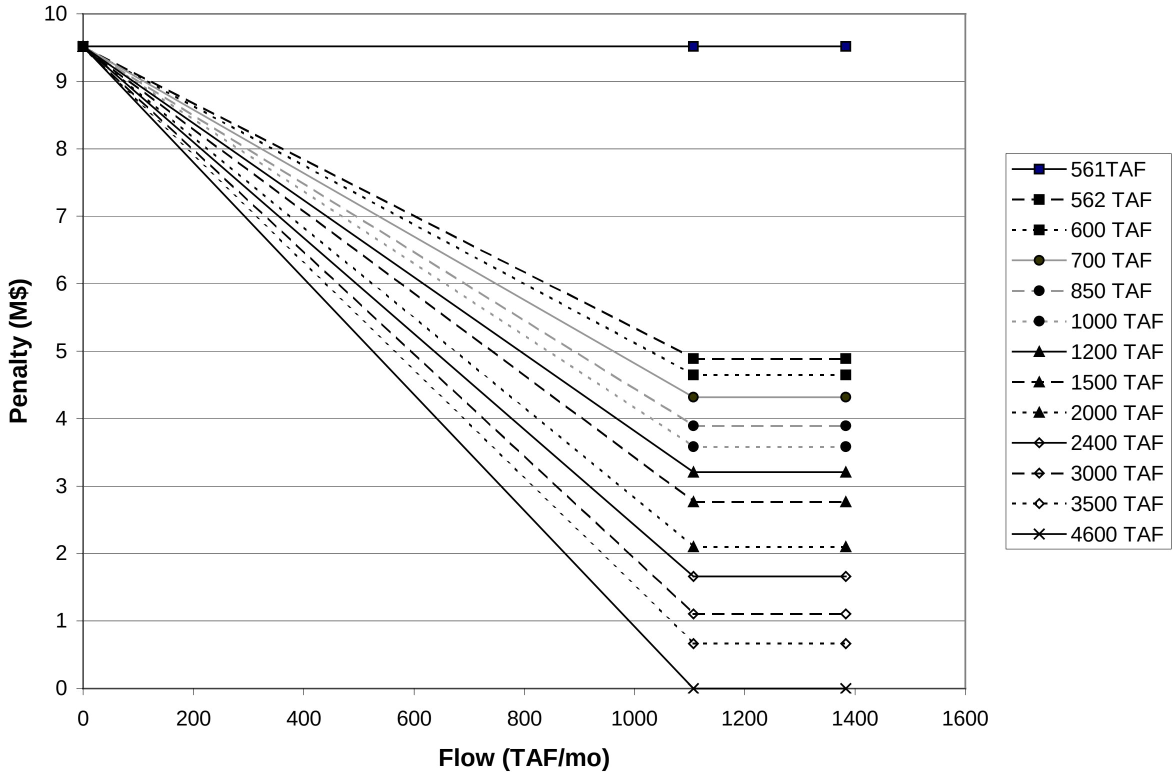


Figure C.5. Penalty curve set for Shasta Reservoir (January)

C.3.3 Iterative variable head (IVH): Variable head

The nonlinear nature of variable-head (i.e., storage) hydropower necessitates the application of algorithms that can approximate nonlinearities with linear relationships. HEC-PRM has incorporated an iterative algorithm for hydropower that successively interpolates within a family of penalty curves, with each curve representing a specific storage level. Figure C.5 graphically displays a set of storage penalty curves for Shasta Reservoir in the SWP system.

The HEC-PRM solver completes an initial iteration. Average reservoir and release rates for a given month are used to approximate power generation benefits using the penalty from the closest storage level. The solver then calculates the rate of change of the penalty per unit of storage based on the adjacent storage curves. The solver updates the network matrix with the new storage values and completes another iteration. This process continues until the solver no longer finds a solution with a lower total cost. See Appendix B of HEC (1993) for details.

This method, although it yields satisfactory results for systems with relatively few hydropower plants, quickly becomes computationally infeasible as hydropower facilities are added (see the Test Results section below). Another method was needed to represent variable-head facilities to complement the limited usability of the iterative algorithm.

C.3.4 Storage and release penalties (SQ): Variable head

Variable-head hydropower plants increase their energy generation as storage and release levels increase. The SQ method approximates a nonlinear variable-head hydropower penalty function through the sum of independent linear storage and release penalties.

The first step is to generate a nonlinear penalty surface that represents all possible combinations of storage levels and releases for a given month using power factors and the nonlinear hydropower equation. Minimum operating flows and maximum flow capacities dictate a range of possible flow values through the power plant; minimum operating storage levels and maximum storage capacities or flood pools bracket possible storage values. Minimizing the operating range for storage and releases provides a better linear approximation. Dividing the operating ranges of storage and releases into 50 and 25 increments, respectively, provides 1,250 points on the penalty surface.

Figure C.6 displays the penalty surface for Shasta Reservoir for the month of January. At low release rates, little variation is seen in the penalty function between low storages and high storages. However, that differential increases as flow rates increase.

For DWRSIM facilities, a best-fit polynomial curve was generated using the storage/power factor pairs given in the DWRSIM code. This polynomial relates average monthly storage values in CALVIN to a specific power factor. Storage and release ranges translate into a penalty matrix, using Equation C.4 (a variation of the hydropower equation in DWRSIM's formulation):

$$B_m = 10 p_m (PF) Q \qquad \text{(C.4)}$$

where B_m is the monthly benefit in K$, p_m is the electricity price in cents/kWh, PF is the power factor, and Q is the release rate in taf/mo. Non-DWRSIM facilities use another variation on the hydropower equation. Published storage and elevation data were used to generate a best-fit polynomial curve. Any storage level can be converted to a reservoir elevation, and $H(S_m)$ is then found by subtracting the average tail water elevation. Equation C.5 calculates the monthly generation benefit:

$$B_m = p_m e Q_m H(S_m) c \qquad \text{(C.5)}$$

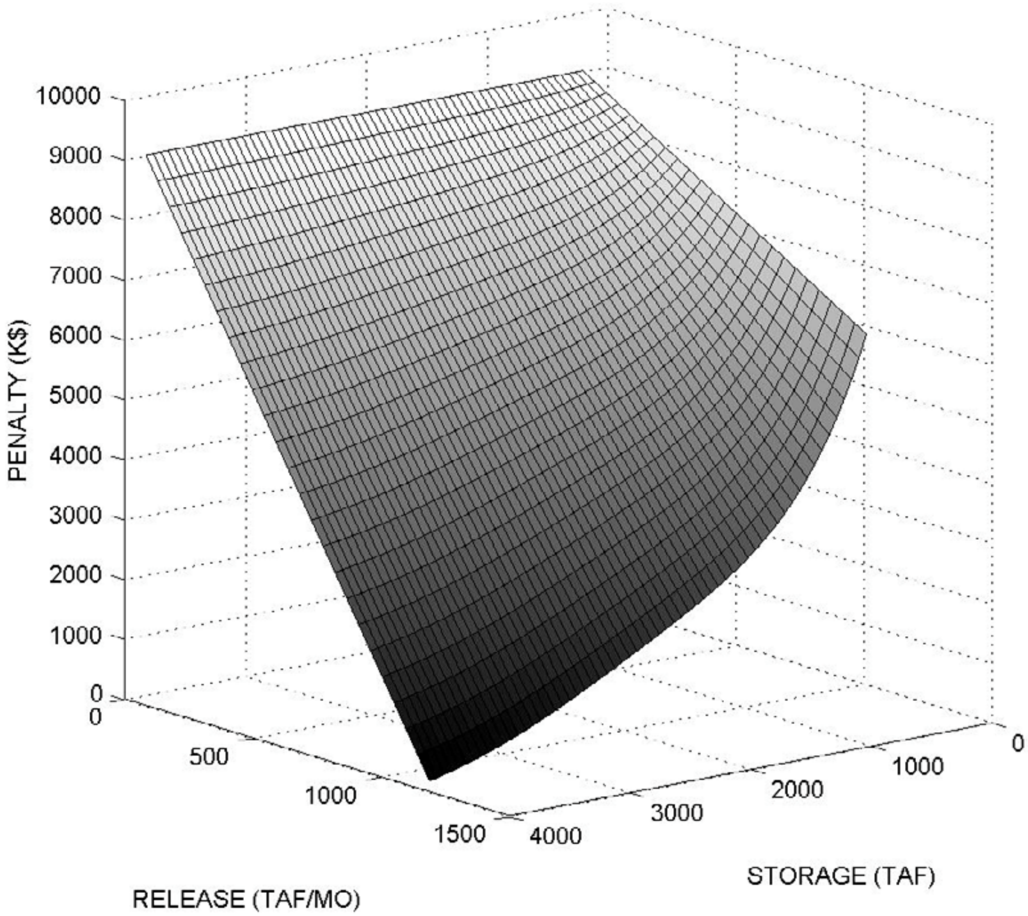


Figure C.6. Nonlinear penalty surface for Shasta Reservoir (January)

where *e* is the assumed efficiency, and *c* is a factor of 0.0102368 (k\$-kW-h-cents^{-1}-taf^{-1}-ft^{-1}), which incorporates the specific weight of water from the hydropower equation and a unit conversion.

The second step of the SQ method uses a least-squares approach to fit a piecewise planar surface to the 1,250 points on the nonlinear penalty surface to give a linear approximation to the penalty function, using the formulation shown in Equation C.6:

$$P_m = P(S_m) + P(Q_m) \qquad \text{(C.6)}$$

A Visual Basic macro initializes an optimization routine in Excel that maximizes the coefficient of determination (R^2 value) of the piecewise planar surface. The decision variables of the routine are the two breakpoints in the piecewise storage curve, along with the slopes and y-intercepts of the three lines in the storage curve and the single release line. The optimized R^2 value indicates how well the planar surface "fits" the nonlinear surface. R^2 values for SQ facilities range from 0.958 to 0.9999+ (see Table C.6).

Figure C.8 displays how a piecewise planar approximation of the penalty curve (meshed surface) for Shasta Reservoir compares to the nonlinear penalty surface (solid surface). The methods are very similar if operated in the midrange of possible storage and release values, but diverge near the extremes.

To complete the piecewise linear penalty, an additional segment is needed. The end point at the lowest storage level (S = 212 taf in Figure C.7) is at the minimum operating pool. The dead pool for Lake Shasta, however, is 116 taf. Below a storage level of 212 taf, the plant would be unable to generate power. Theoretically, the penalty function should jump vertically to the maximum level at the minimum operating pool, and then extend horizontally at that maximum penalty level to the dead pool (see Figure C.9, line "A"). Simply extending a segment from the minimum operating pool to the maximum penalty at dead pool (Figure C.9, line "B") would greatly underestimate the penalty for storage operations in this range. A compromise penalty segment is shown as line "C," where the end point of the penalty function located at the dead pool is placed at twice the maximum penalty level. Although there is a risk of overestimating penalties using the C penalty segment, this approach is necessary to maintain a convex penalty function.

As noted earlier, SQ penalty functions fit nonlinear penalty surfaces more accurately where storage head is a small proportion of the total head of the facility. Thus, the R^2 value reflects the linearity of the facility in consideration. Representing variable-head facilities with the SQ method over the IVH method sacrifices some accuracy but permits feasibility of large-scale systems analysis by reducing computational time.

C.4 Test Results

Because the effectiveness of the IVH and SQ variable-head methods for a large-scale model was uncertain, two tests were performed on a portion of the CALVIN model. Run times and realistic, justifiable operations were the performance indicators for the two methods.

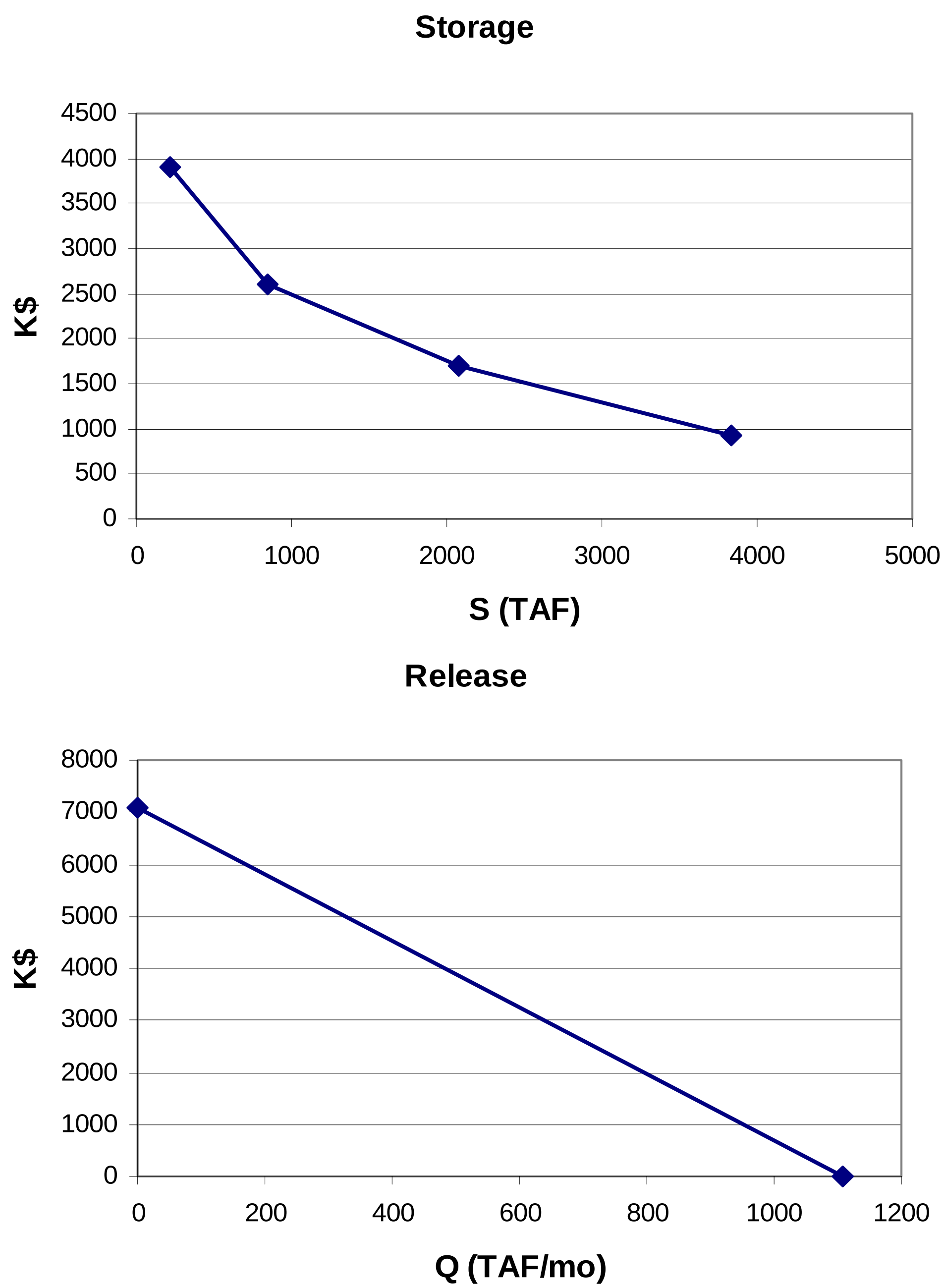


Figure C.7. Shasta Reservoir storage and release penalties for SQ method (July)

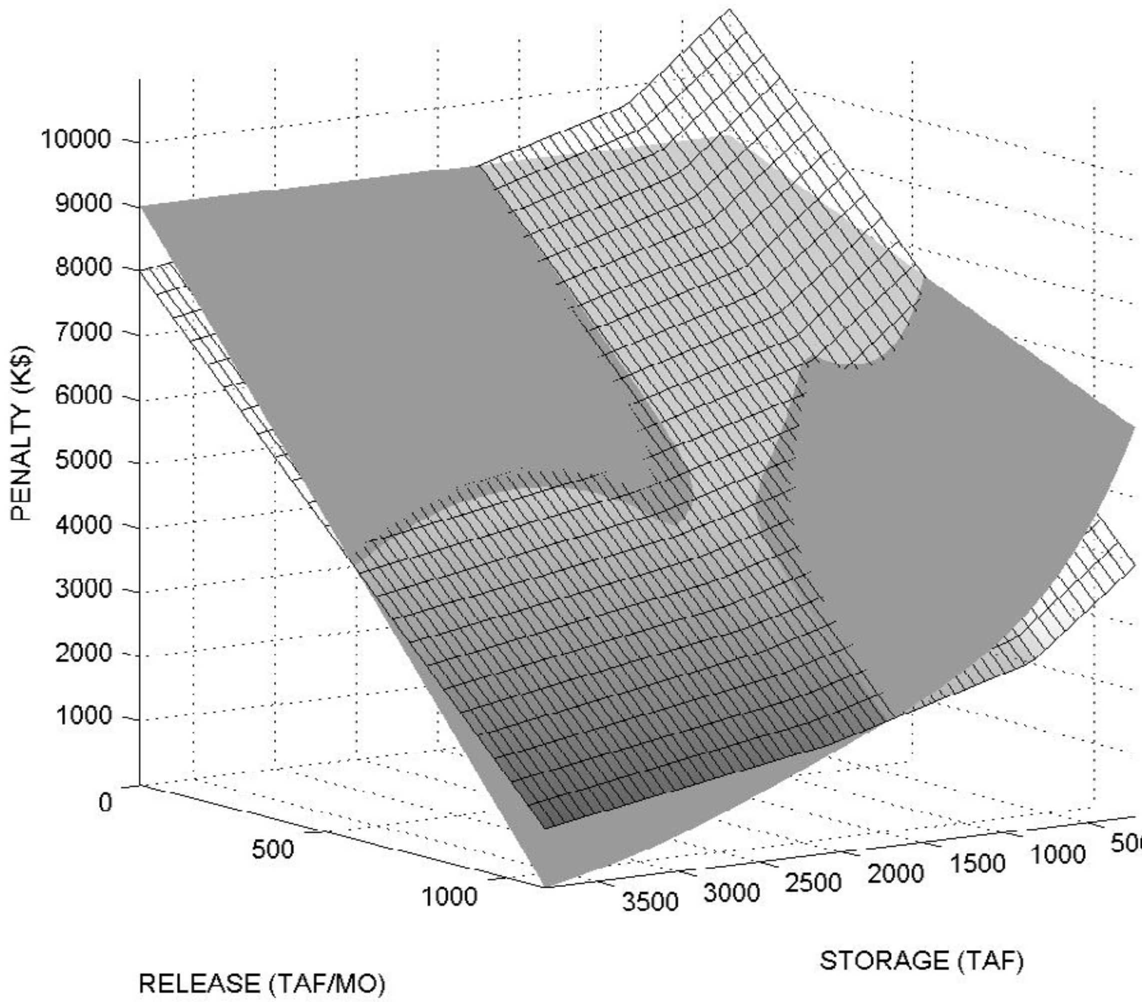


Figure C.8. SQ penalty surface comparison for Shasta Reservoir

C.4.1 Test 1: IVH method

Test 1 was used to discern the sensitivity of CALVIN to varying degrees of detail in the IVH representation of variable-head hydropower. Using only the Upper Sacramento Valley region of the CALVIN model (region 1) for this test enhanced the interpretability of the results. An unconstrained model run for region 1 from the CALVIN CALFED study provided a basis for comparison.

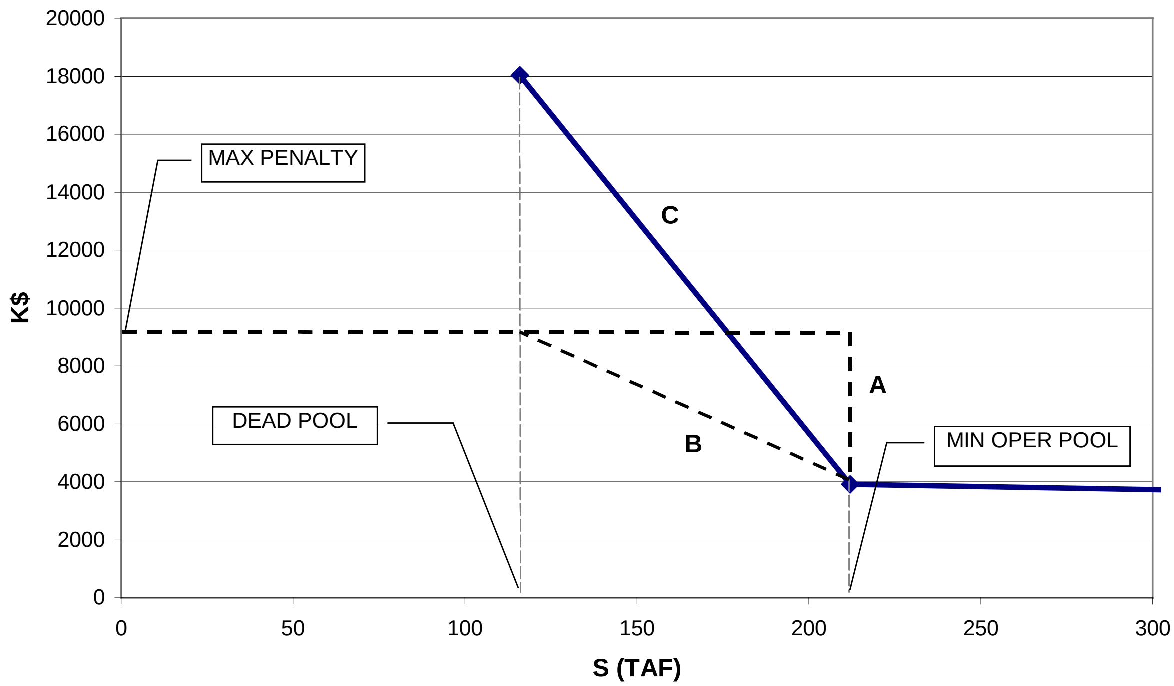


Figure C.9. Left-most penalty segment

Shasta and Clair Engle reservoirs were modeled with HEC-PRM's iterative algorithm, but all other facility representations remained unchanged from the unconstrained "base case." DWRSIM power factor/storage paired data translated directly into a family of storage-based penalty curves (see Figure C.10).

Subsequent runs changed the number of storage curves used for the two reservoirs, as described in Table C.2. In a similar manner to the PWL method described above, a piecewise linear curve fitting a best-fit polynomial line of the storage/power factor relationship mimicked the linear interpolation that HEC-PRM performs (see Figure C.11). The breakpoints of the best-fit piecewise linear approximation indicate which storage levels should be used for different numbers of storage curves. The points shown in Figure C.11 translate the original 13 storage levels from DWRSIM into the 6 storage levels shown in Figure C.12. By varying the number of segments in the piecewise linear approximation, families of varying numbers of storage penalty curves can be generated and tested.

Storage (taf)	Power Factor
561	0
562	0.209
600	0.22
700	0.235
850	0.254
1000	0.268
1200	0.285
1500	0.305
2000	0.335
2400	0.355
3000	0.38
3500	0.4
4600	0.43

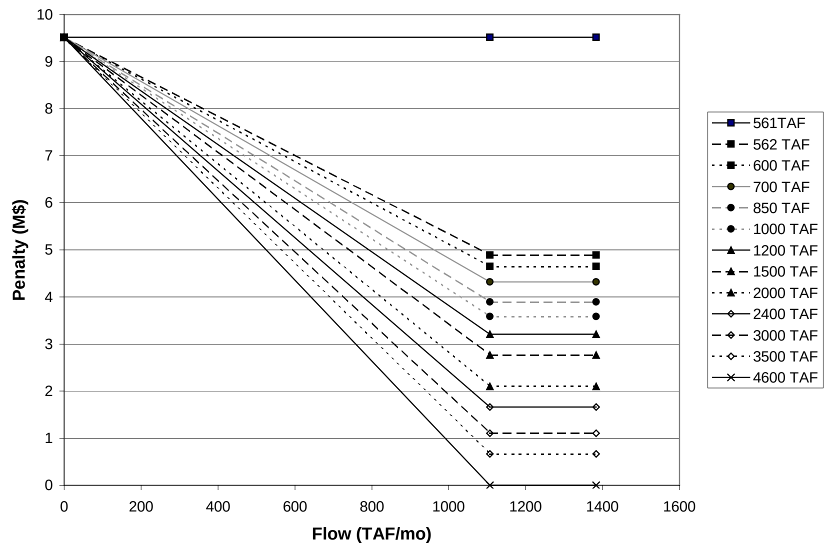


Figure C.10. DWRSIM power factor/storage pairs for Shasta Reservoir

Table C.2. IVH test run descriptions

Run 1	Unconstrained combined regions 1 and 2 model. No variable-head hydropower.
Run 2	IVH variable-head method applied to Shasta and Clair Engle reservoirs, using DWRSIM power factors. Shasta: 13 storage curves; Clair Engle: 10 storage curves.
Run 3	IVH method. Both Shasta and Clair Engle: 6 storage curves.
Run 4	IVH method. Both Shasta and Clair Engle: 26 storage curves.
Run 5	IVH method. Both Shasta and Clair Engle: 5 storage curves.

Test results show little difference among runs 2 through 5, as Table C.3 shows. Incorporating the IVH method, even on only two reservoirs on a small portion of the entire system, causes a marked increase in run time. Results indicate that the model run times are relatively insensitive to the number of storage penalty curves used on a fixed number of variable-head facilities, but are highly sensitive to the number of facilities modeled with the iterative algorithm. These results suggest the necessity of minimizing the number of facilities represented with the IVH algorithm.

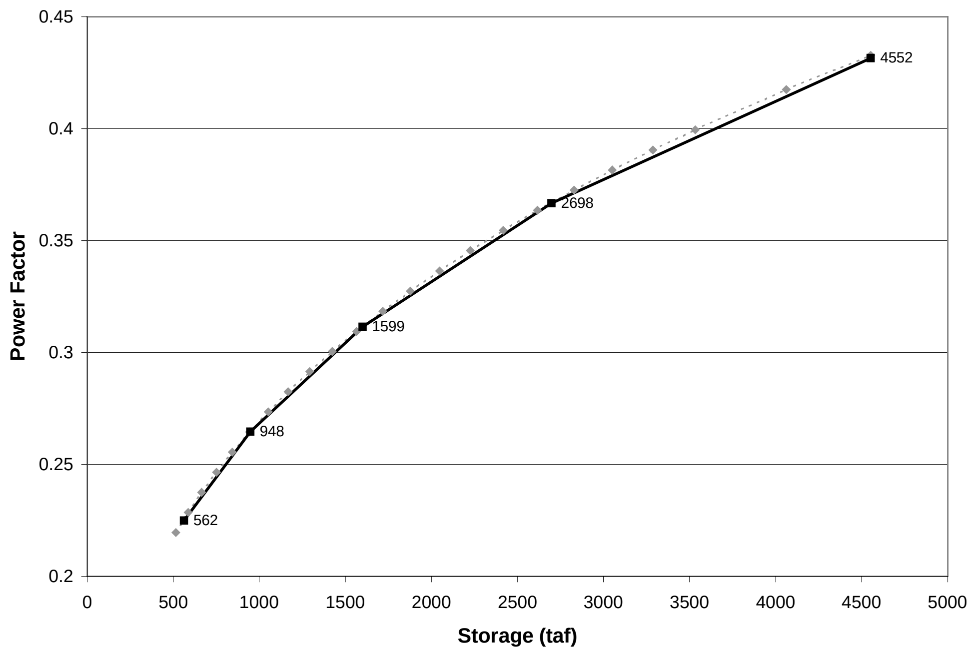


Figure C.11. Storage/power factor interpolation

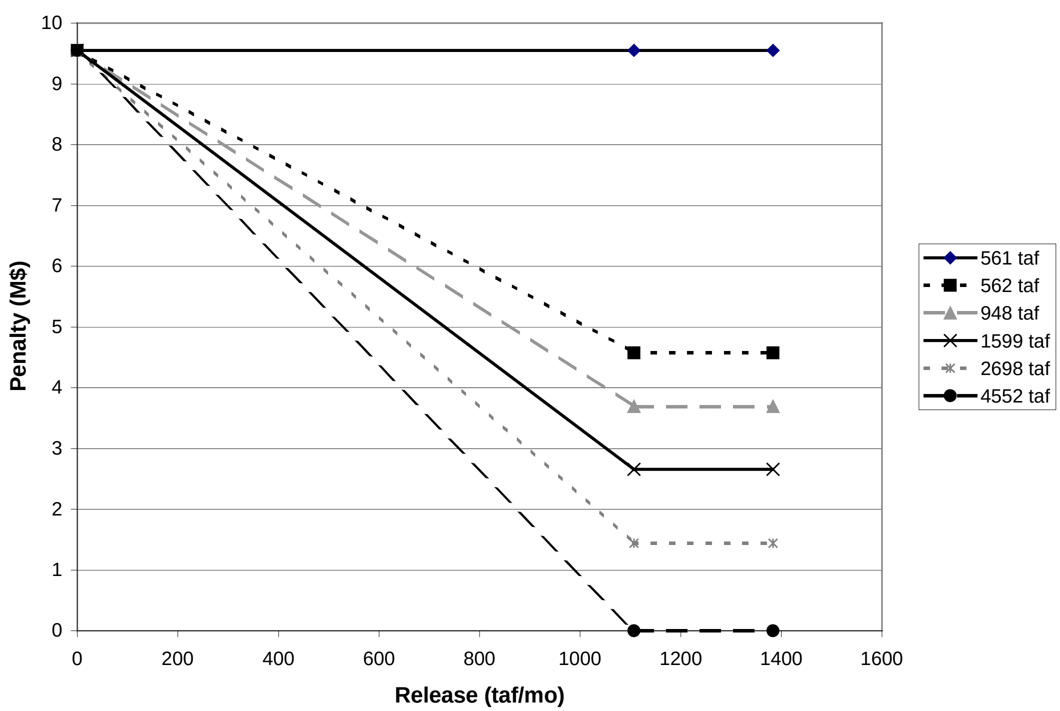


Figure C.12. Revised storage penalties — Shasta Reservoir

Table C.3. IVH test results

Run	Number of hydropower iterations	Time (h)
1	n/a	3.7
2	15	10.6
3	16	10.9
4	20	12.9
5	17	10.6

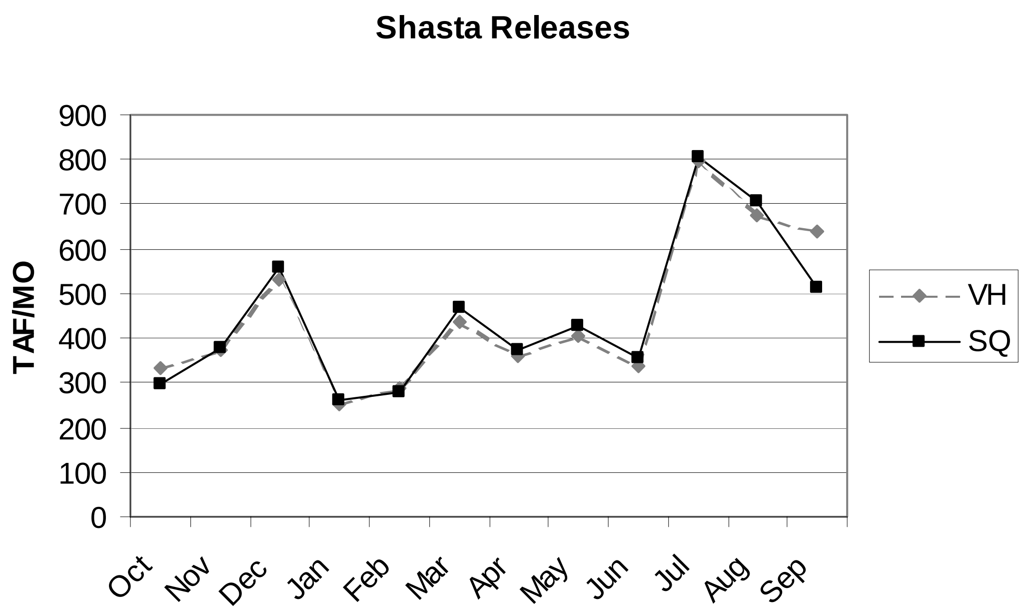
C.4.2 Test 2: Comparing the SQ and IVH methods

An earlier combined run of the Upper Sacramento Valley and Lower Sacramento Valley and Bay Delta regions of CALVIN (regions 1 and 2) from the CALFED modeling effort provided a base case for this test. This confined the test to a smaller geographical region while still capturing a significant portion of the state's generating capacity, because most of the hydropower capacity in the state is located north of the delta.

In the first run, flow ("fixed-head") penalties were placed on Keswick, Nimbus, Thermalito Diversion, and Thermalito Fore/Afterbay. Whiskeytown, New Bullards Bar, Folsom, and Englebright reservoirs utilized the SQ representation for variable-head hydropower. Shasta, Oroville, and Clair Engle reservoirs, the largest and most nonlinear facilities in the region, were modeled using the IVH algorithm. In the second run, Shasta, Oroville, and Clair Engle were converted to the SQ method.

Initial run time results showed the substantial computational "savings" of using the SQ method for variable-head facilities. Run 1 lasted 17.9 h; run 2 lasted 10.7 h. This time differential would be expected to increase as the remaining regions to the south of the delta are included in statewide CALVIN runs.

Variable-head storage and release comparisons between the runs show the mixed effectiveness of the SQ method (see Figures C.13 through C.15). Shasta is the largest reservoir in the state, and the R^2 value for Shasta and that of smaller Clair Engle are 0.958 and 0.963, respectively. Test results reveal that the IVH and SQ methods differ little for Shasta and Clair Engle operations. An average monthly storage level of 3.581 maf for Shasta under the SQ representation exceeds the IVH storage by only 51 taf. Similarly, SQ average monthly storage for Clair Engle differs from the IVH storage by 55 taf (see Figure C.14). Similar average storages are consistent with only slight variations in average monthly releases for both reservoirs. The SQ method appears to be an acceptable alternative for the IVH representation for Shasta and Clair Engle, despite their size and the nonlinearity of their hydropower penalty functions.



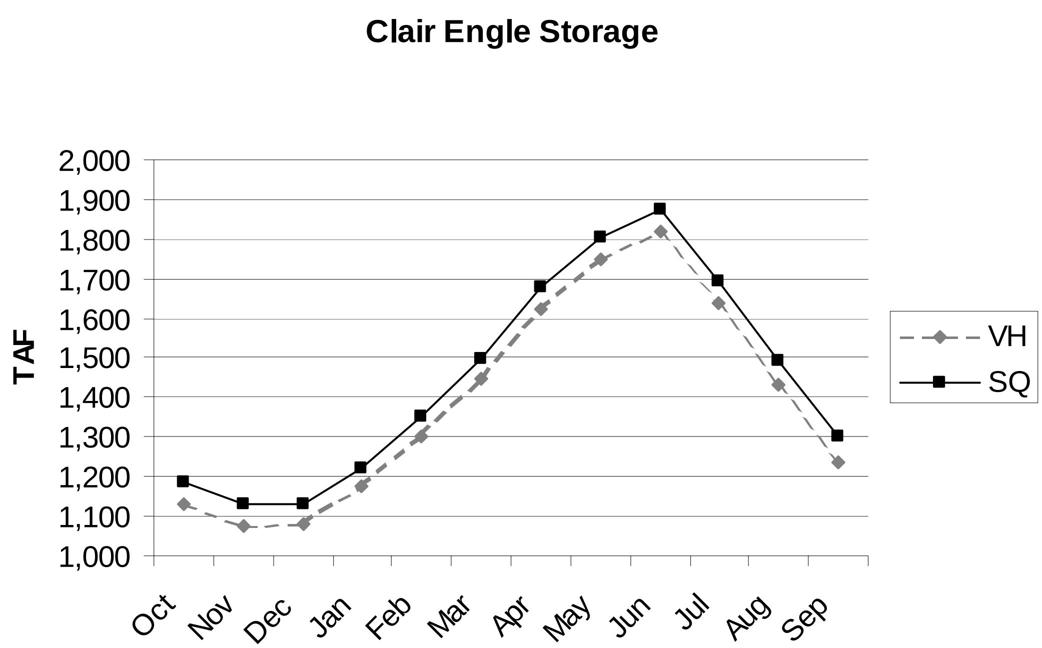


Figure C.13. Shasta variable head method comparison

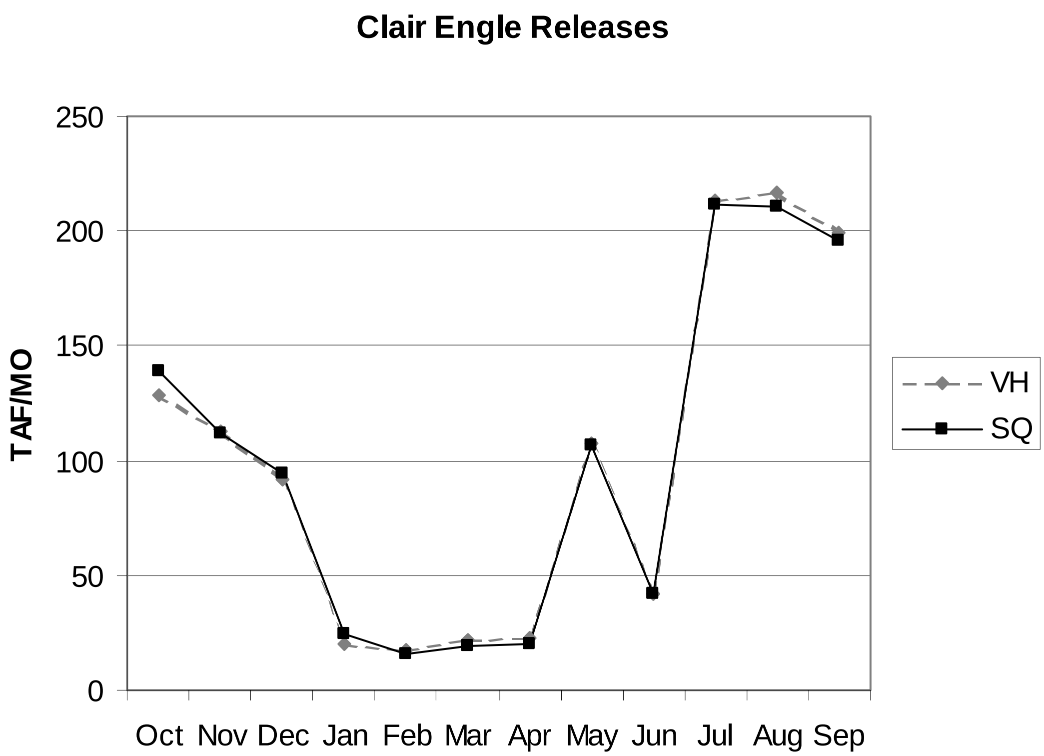
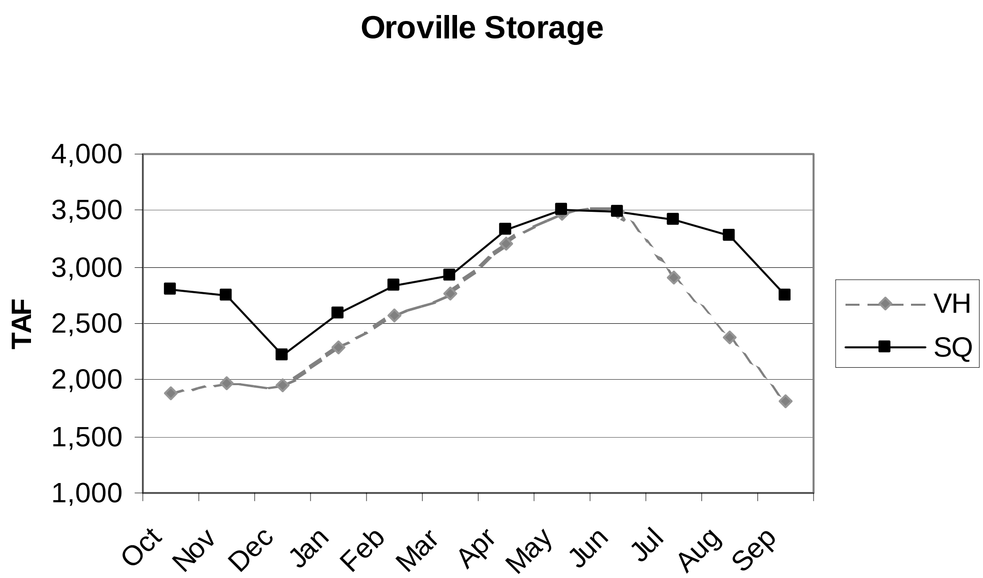


Figure C.14. Clair Engle variable head method comparison

In contrast, the operation of Lake Oroville differs sharply between the two variable-head methods. The average storage level for the SQ representation exceeds the IVH method by 435 taf, with much larger differences occurring in the months from July to November (see Figure C.15). Releases follow a similar disjointed pattern, where large releases are offset by as much as 5 months. These results support the conclusion that reservoir size or the degree of nonlinearity of the hydropower function are not necessarily the factors that determine the effectiveness of the SQ approximation. The residuals between the SQ linear approximation and the nonlinear penalty function are typically positive at higher storage values and lower release rates, where the system tends to operate variable-head facilities for most of the year. Economic values of storage, then, tend to run higher for most of the year. In portions of the system where hydropower facilities are well connected to other supplies, the system may have the flexibility to re-operate reservoirs and groundwater basins to maximize the storage of the SQ facility, even if the value of storage on that reservoir is not significantly higher. This appears to be the case with Lake Oroville in the test runs.



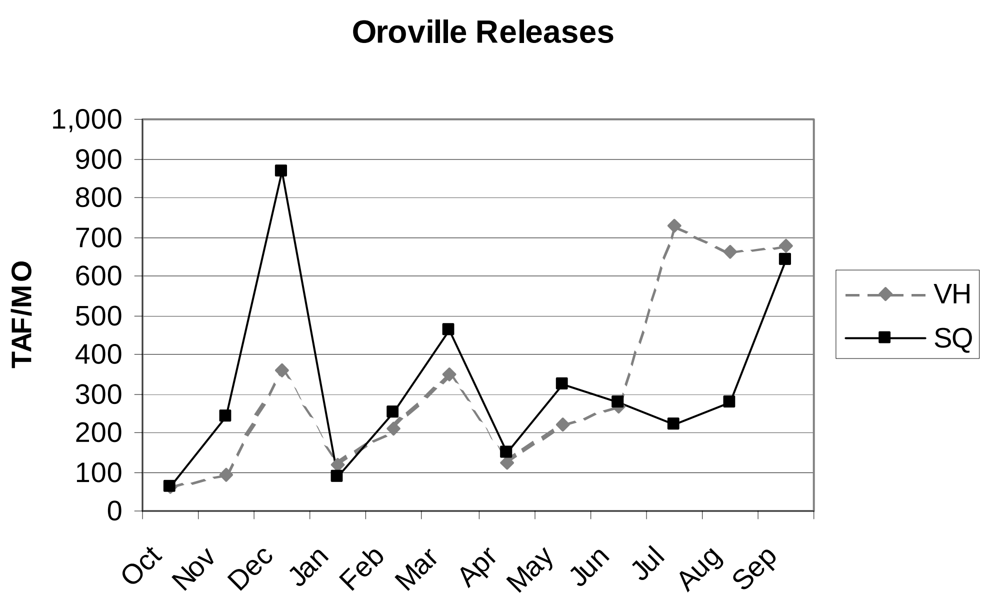


Figure C.15. Oroville variable head method comparison

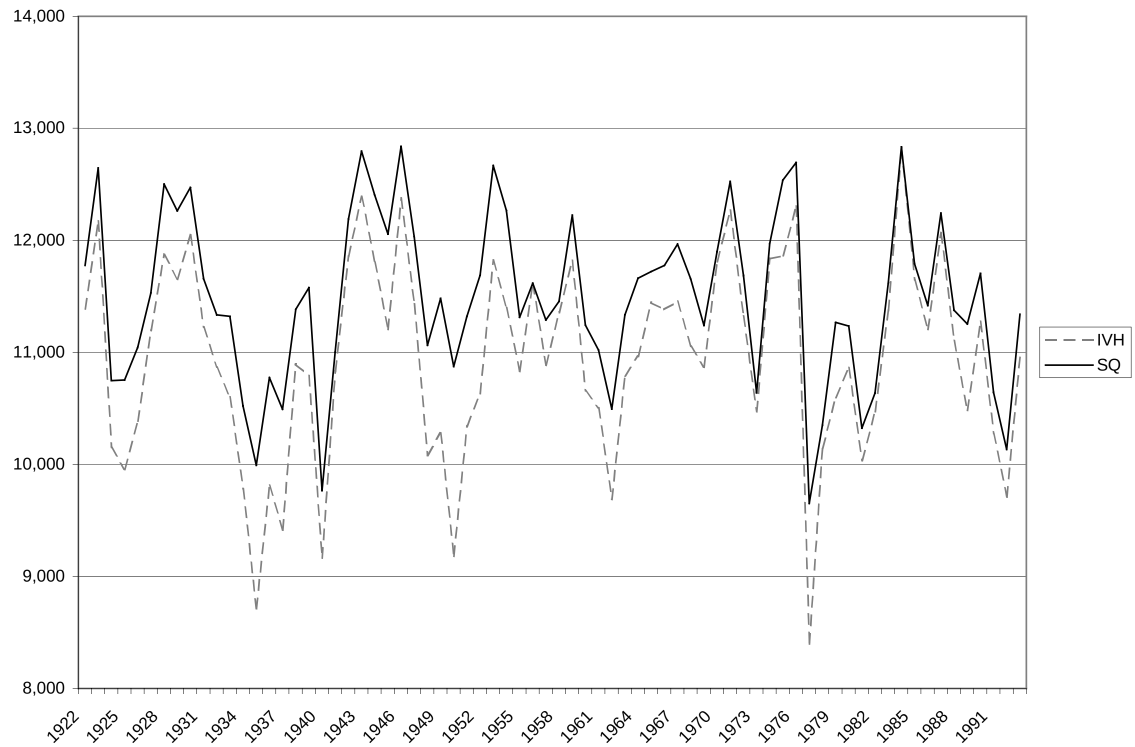


Figure C.16. Total regional surface storage (annual average)

As reflected in Figure C.16, total regional surface storage increases under the SQ representation. Average monthly surface storage in the SQ run is almost 11.5 maf, compared to 10.9 maf in the IVH run. Of the 538 taf difference, 435 taf is due to the disparity in Oroville storage.

Figure C.17 shows how small differences in values of hydropower generation can dramatically affect operations. Oroville attempts to maximize hydropower production by reserving storage until a release is necessary. In this north-of-delta analysis, these releases occur mainly in December as a large pulse through the delta. Smoother operations can be expected if downstream demands (south-of-delta) are allowed access to the water.

Marginal values on storage capacity expansion vary slightly between the two representations. Differences of the nonzero marginal value of storage range from $0.27 per acre-ft expansion for Clair Engle reservoir to $0.37 per acre-ft for Oroville reservoir.

Figure C.17. Difference in delta outflow (SQ-IVH)

C.5 Hydropower Facilities

Table C.4 lists all the hydropower facilities included in CALVIN in this phase of model development. These power plants either have greater than 30 MW of generating capacity or were previously modeled in the DWRSIM hydropower postprocessor.

With the exception of Castaic Lake, the largest facilities are located north of the delta, in regions 1 and 2 of the CALVIN model (see Lund, 2002, for regional descriptions). Power plants in Southern California mainly comprise high-head facilities on the Los Angeles Aqueduct or energy recovery plants on the SWP system. Along with the CDWR and the U.S. Bureau of Reclamation (USBR), operators include several irrigation districts, urban utilities, and conservation districts.

Table C.4. CALVIN hydropower facilities

Name	Location	Operator	Capacity (MW)	CALVIN region
Shasta	Shasta Res.	CVP	629	1
Spring Creek	Spring Creek Tunnel	CVP	180	1
Judge Francis Carr	Clear Creek Tunnel	CVP	154.4	1
Trinity	Trinity R., Clair Engle Res.	CVP	140	1
Keswick	Sacramento R. below Shasta	CVP	117	1
Hyatt	Feather R., Oroville complex	SWP	644.25	2
Colgate	New Bullards Bar Res.	YCWA	325	2
Folsom	American R., Folsom Res.	CVP	198.7	2
Thermalito	Feather R., Oroville complex	SWP	115	2
New Narrows	Yuba R., Englebright Res.	YCWA	49	2
Nimbus	American R.	CVP	13.5	2
Thermalito Divers.	Feather R., Oroville complex	SWP	3	2
Gianelli	San Luis/ Cal. Aqueduct	SWP, CVP	424	3
New Melones	Stanislaus R., New Melones Res.	CVP	300	3
Don Pedro	Tuolumne R., Don Pedro Res.	TID,[a] MID[b]	203.2	3
Dion R. Holm	Tuolumne R., Cherry Lake	HHW&P[c]	156.8	3
R C Kirkwood	Tuolumne R., Hetch Hetchy Res.	HHW&P	121.9	3
Moccasin	Tuolumne R.	HHW&P	103.6	3
New Exchequer	Merced R., Lake McClure	MID[d]	94.5	3
O’Neill	San Luis/Cal. Aqueduct	CVP	25.2	3
Pine Flat	King’s R., Pine Flat Res.	KRCD[e]	190	4
Castaic	Off Cal. Aqueduct, Castaic Lake	SWP, LADWP	1,247	5
Devil Canyon	Cal. Aqueduct	SWP	280	5
William E. Warne	Pyramid Lake	SWP	78.2	5
San Francisquito 1	Los Angeles Aqueduct	LADWP	75.5	5
San Francisquito 2	Los Angeles Aqueduct	LADWP	47	5
Control Gorge	Inyo, Owens River	LADWP	38	5
Middle Gorge	Mono Basin	LADWP	38	5
Upper Gorge	Mono Basin	LADWP	36	5
Mojave Siphon	Cal. Aqueduct	SWP	32.4	5
Drop 4	All American Canal	IID[f]	18.05	5
Alamo	Cal. Aqueduct	SWP	17	5

a. Turlock Irrigation District.
b. Modesto Irrigation District.
c. Hetch Hetchy Water & Power.
d. Merced Irrigation District.
e. King’s River Conservation District.
f. Imperial Irrigation District.

Almost all fixed-head facilities (shown in Table C.5) utilize DWRSIM representations, except for the Hetch Hetchy and Los Angeles Aqueduct systems. Flow factors from DWRSIM translate directly into piecewise linear penalty functions for Keswick, Thermalito Fore/Afterbay and Diversion Dam, and Nimbus power plants. A flow/head relationship gleaned from DWRSIM's code was used to generate three-segmented piecewise linear penalties for the Castaic and Warne power plants. Data for the Los Angeles Department of Water and Power (LADWP) plants were difficult to obtain; models of the San Francisquito and Gorges facilities use heads reported in Jenkins (2001) and an assumed overall efficiency of 0.85.

Table C.6 lists the 15 variable-head power plants included in CALVIN, how they are represented, and their data sources. Three of the largest power plants on Shasta reservoir, Clair Engle reservoir, and Lake Oroville utilize the IVH algorithm, because test results indicate susceptibility to operational distortion with the storage/release penalty method. Storage levels were taken directly from storage- and power-factor paired data in DWRSIM.

Flood pool levels for many of the SQ reservoirs (which are modeled as monthly upper bounds on storages in CALVIN) aided in narrowing operational storage ranges, increasing the fit of the piecewise planar approximation. Furthermore, minimum instream flows directly downstream of the New Don Pedro and New Exchequer facilities served as operational lower bounds. Where institutional or regulatory constraints were not imposed, physical capacities were used in determining storage and release ranges.

Table C.5. Fixed-head hydropower facilities

Name	CALVIN link name	Method	Data source
Keswick	D5_D73	PWL	DWRSIM
Thermalito Fore/Afterbay	SR-7_C25	UC	DWRSIM
Nimbus	D9_D85	PWL	DWRSIM
Thermalito Div. Dam	C23_C25	UC	DWRSIM
Moccasin	C44-C88	UC	SFPUC (2002)
O'Neill	ONeill PWP_D712	UC	DWRSIM
Castaic[a]	Cast PWP_D887	PWL	DWRSIM
Devil Canyon	Devil PWP_C129	UC	DWRSIM
Warne	Warne PWP_SR-28	PWL	DWRSIM
San Francisquito 1&2	Owens 2 PWP_C122	UC	CALVIN CALFED
Gorges[b]	Owen1 PWP_C114	UC	CALVIN CALFED
Mojave Siphon	Mojave PWP_SR-25	UC	DWRSIM
Drop 4	AAC PWP_C151	UC	CALVIN CALFED
Alamo	Alamo PWP_D868	UC	DWRSIM

a. See note on Table C.4.
b. Includes Upper, Middle, and Control Gorge plants.

Table C.6. Variable-head hydropower facilities

Name	Reservoir	Release	Method	R^2 value	Data source
Shasta	SR-4	SR-4_D5	SQ	0.958	DWRSIM
Spring Creek	SR-3	SR-3_D5	SQ	0.995	DWRSIM
Carr	SR-3	D94&D40_ SR-3	SQ	0.999+	DWRSIM
Trinity	SR-1	SR-1_ D94&D90	SQ	0.963	DWRSIM
Hyatt[a]	SR-6	SR-6_C23	IVH	N/A	DWRSIM
Colgate	SR-NBB	SR-NBB_C27	SQ	0.996	USGS (1994), Bookman-Edmonston (2000), YCWA (2002)
Folsom	SR-8	SR-8_D9	SQ	0.986	DWRSIM
New Narrows	SR-EL	SR-EL_C28	SQ	0.999	DWR (YUBA)
Gianelli[a]	SR-12	Gianelli PWP_D816	IVH	N/A	DWRSIM
New Melones	SR-10	SR-10_D670	SQ	0.963	DWRSIM
Don Pedro	SR-81	SR-81_D662	SQ	0.965	SFPUC (2002), Lund (1999)
Holm	SR-LL-LE	SR-LL-LE_SR-81	SQ	0.999+	SFPUC (2002), USBR (1987)
Kirkwood	SR-HHR	SR-HHR_C44	SQ	0.997	USBR (1987), SFPUC (2002), USGS (1994)
New Exchequer	SR-20	SR-20_D642	SQ	0.963	USGS (1994), Klein (2002)
Pine Flat	SR-PF	SR-PF_C51	SQ	0.965	USGS (1994), Richards (2002)

a. Castaic, Gianelli, and Hyatt powerplants are actually pump/storage facilities. Water released at peak periods of the diurnal cycle can be pumped from the afterbay back into the reservoir in off-peak times. Models of these three plants at this time use the DWRSIM representations of these facilities because pumped/storage behavior is difficult to represent in CALVIN's network flow algorithm.

Each of the DWRSIM-based SQ models translated the model's paired data into a best-fit polynomial, allowing storage and release ranges to be evenly discretized. Maximum flow rates and minimum and maximum operating pools also came directly from DWRSIM data.

Parameters for the Colgate and New Narrows power plants were derived from the Bookman-Edmonston study (2000) on the Yuba River, and from CDWR's Bear River study. These planning studies were based on HEC-3 and HEC-5 simulations. Physical parameter data on Pine Flat, Colgate, and New Exchequer were obtained from personal contacts at several irrigation districts and water agencies (Klein, 2002; Richards, 2002; Yuba County Water Agency [YCWA], 2002).

Because data on physical parameters were sparse, hydropower parameters for the Hetch Hetchy system and the New Don Pedro power plant were derived using published operational data. Regression analysis utilized known parameters gleaned from sources such as USBR (1987) to derive the unknown parameters (namely efficiency and average tail water elevation).

Further documentation will be available on the future CALVIN CEC disk, and can be ordered through Jay Lund in the Civil and Environmental Engineering Department of the University of California, Davis (http://cee.engr.ucdavis.edu/faculty/lund).

C.6 Potential Improvements

C.6.1 Pump/storage facility representation

The Castaic, Hyatt, and Gianelli power plants, which are several of the largest in the state, are pump/storage facilities, although CALVIN treats them as conventional hydroelectric plants. In actuality, operational criteria are based on daily energy price fluctuations. Difficulties in capturing diurnal operations in a monthly time step model are exacerbated by the limitations of CALVIN's network flow solver. Representation of pump/storage facilities may be possible, although it may involve operational assumptions that may limit the efficacy of such an approach. It may be possible to represent diurnal pumped storage energy generation value as a function of monthly storage, which partially determines peak-generation capacity for such plants.

C.6.2 Capacity values on storage

CALVIN currently models the economic benefit of power generation, but excludes system reliability considerations. In reality, reservoir operators are compensated for maintaining water in storage and excess turbine capacity, both of which are held in reserve in case of emergency (such as when several power plants shut down concurrently). A more accurate depiction of the true economic benefit of hydropower would include values of generating capacity.

C.6.3 Electricity pricing

Most of the large storage facilities with means of regulating inflows or releases (through forebays or afterbays) are operated as peaking plants. CALVIN uses an average monthly wholesale price, eliminating the distinctions between peaking, intermediate, and base load plants. Such an approach potentially underestimates the economic benefit from peaking facilities and overestimates benefits from base load plants. Further thought is needed to discover ways of representing price differentials without relying heavily on operational assumptions.

C.6.4 Including upstream facilities currently outside the boundaries of CALVIN

Although limited in storage capacity, a number of large hydropower systems exist above the boundaries of the CALVIN model. Some examples include Southern California Edison’s Big Creek system on the Upper San Joaquin River, which has a combined generating capacity of 1 GW, and Pacific Gas & Electric’s 810-MW Shasta watershed system. Including these upstream facilities, although adding to CALVIN’s robustness, presents formidable modeling obstacles. Historical unimpaired hydrology data are largely unavailable. Modeling these systems may be possible, but access to privately held hydrologic data is necessary for the sake of accuracy.

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Appendix VII — Attachment D

2002 Environmental Constraints

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Tables

Abstract

Unlike agricultural and urban demands, environmental demands in the CALVIN model are not represented in terms of the economic value of deliveries. Instead, environmental demands are represented as monthly minimum instream flow requirements on rivers, Sacramento-San Joaquin delta reaches, carryover storage at Shasta, and minimum water supply requirements for refuge areas. These requirements vary by month and year and are intended to represent the minimum acceptable amount of water for environmental uses at their current level of development. Current environmental requirements include Central Valley Project Improvement Act (CVPIA) actions such as B2 and Level 4 refuge demands and the Environmental Water Account (EWA). This attachment explains CALVIN's approach and assumptions in modeling minimum instream flow requirements and refuge demands, as well as the associated limitations. In addition, this attachment documents an updated version of earlier representations of environmental flows in the CALVIN model.

D.1 Minimum Instream Flow Requirements

Although minimum instream flow requirements are used throughout California, CALVIN's aggregated modeling approach limits these flow constraints to those directly applicable to a canal or river reach included on the CALVIN schematic. Many minimum instream flow requirements vary monthly and by year type. Year types (wet, above normal, normal, below normal, dry, and critical) are classified by some type of index. A monthly pattern of flow requirements then corresponds with each year type, and a time series of minimum flows can be constructed from year types for the 1922-1993 hydrologic sequence modeled in CALVIN. Other more complex requirements depend on concurrent storage, flow, water quality, or other conditions. These latter relationships cannot be represented dynamically in CALVIN's network flow programming formulation. Instead, CALVIN uses a predetermined time series of minimum flows from a simulation of current conditions. Minimum flow requirements that depend on concurrent conditions were taken from a simulation of the California Department of Water Resources model CALSIM II that most closely matches the assumptions in CALVIN (CALSIM II EWA BST_2001LOD_Gmodel) run. Table D.1 summarizes the links in CALVIN with the minimum instream flow requirements and indicates each requirement's data source and basis.

D.1.1 CALVIN approach

The decision to place (or not to place) a minimum instream flow requirement on any particular river was based primarily on whether that river was given such a requirement in the Department of Water Resources' CALSIM II model (DWR, 2002). Although most of the minimum instream flow requirements were developed from the lookup tables in the CALSIM II input data files,

Table D.1. CALVIN river reaches with environmental flow constraints

River	CALVIN links	Location	Data source	Flow values (cubic feet per second [cfs])			Function of
				Minimum	Maximum	Average	
American	D64_C8	From urban diversions to mouth	CALSIM II Arcs C301, C302, and C303	188	500	315	Year type, 40-30-30 Sacramento Basin Index[a]
American	D9 to D64	Below Nimbus Dam to urban diversions	Time series from CALSIM II output Arc C9	250	3,000	1,928	Complex concurrent conditions
Calaveras	SR-NHL to C41	Release from New Hogan Dam down to month	CALSIM II Arc C92	2	2	2	Constant monthly minimum instream flow requirement
Clear Creek	SR-3_D73	Below Whiskeytown Lake	Time series from CALSIM II output Arc C3	100	215	168	Complex concurrent conditions
Delta outflow	Required Delta Outflow_Sink	Delta outflow into San Francisco Bay	Time series DWRSIM 514 output for CP541	3,000	28,468	7,771	Complex concurrent conditions
Feather	C23_C25	Above Thermalito return	CALSIM II Arc C200A	600	600	600	Constant monthly minimum instream flow requirement
Feather	C25_C31	Below Thermalito return to confluence with Bear River	CALSIM II output for Arcs C203, C204, and C205	1,000	1,700	1,294	Complex concurrent conditions

Table D.1. CALVIN river reaches with environmental flow constraints (cont.)

				Flow values (cubic feet per second [cfs])			
River	**CALVIN links**	**Location**	**Data source**	**Minimum**	**Maximum**	**Average**	**Function of**
Feather	C32 to D43	From Bear River confluence to mouth	Time series from CALSIM II input Arc C223	748	1,710	1,188	Complex concurrent conditions
Merced	D645_D646	Above confluence with San Joaquin River	Time series from CALSIM II input Arc C562	0	252	162	Year type, 60-20-20 San Joaquin Index[b]
Merced	D649_D695	Above confluence with San Joaquin River	Time series from CALSIM II input Arc C567	16	228	109	Year type, 60-20-20 San Joaquin Index[b]
Mokelumne	SR-CR to D515	Releases from Camanche Reservoir to delta	CALSIM II Arcs C91, C502, and C503	0	467	123	Year type, 60-20-20 San Joaquin Index[b]
Mono Basin	SR-GL_ SR-ML	Aggregate of Rush, Parker, Walker, and Lee Vining creeks	SWRCB, 1994, Decision 1631	72	137	102	Mono Basin projected inflow
Owens Lake	C120_SR-OL	Owens Lake dust mitigation requirements	Modified from Great Basin Unified Air Pollution Control District (GBUPCD, 1998)	15	146	55	Remediation measures
Sacramento	D5_D73	Below Keswick Reservoir	Time series from CALSIM II output Arc C3	3,000	11,000	5,600	Complex concurrent conditions

Table D.1. CALVIN river reaches with environmental flow constraints (cont.)

River	CALVIN links	Location	Data source	Flow values (cubic feet per second [cfs]) Minimum	Maximum	Average	Function of
Sacramento	D76a to C69	Below Red Bluff	CALSIM II Arc C112	3,250	3,900	3,298	Year type, Shasta Index[c]
Sacramento	D61_C301	Navigation control point	Time series from CALSIM II output Arc C129	3,500	5,000	4,545	Complex concurrent conditions
Sacramento	D503_D511	At Hood	Time series from DWRSIM 514 input	5,000	5,000	5,000	Constant time series, monthly varying
Sacramento	D507_D509	Rio Vista requirements	CALSIM II Arc C405	0	4,500	1,327	Year type, Sacramento Index[a]
San Joaquin	D676_D616	Below confluence with Stanislaus at Vernalis	State Water Resources Control Board (SWRCB, 1999)	0	6,201	1,434	Complex concurrent conditions
Stanislaus	D653a_D653b	Below Goodwin	CALSIM II Arc C16	0	1,500	366	New Melones forecast and pulse flow
Trinity	D94&D40_SinkD94	Trinity below Lewiston Dam	CALSIM II Arc C100	300	4,709	835	Year type, Trinity index[d]
Tuolumne	D662_D663	Below Turlock ID Irrigation District diversion	Time series from CALSIM II output Arc C540	50	4,474	385	Complex concurrent conditions
Tuolumne	D664_D683	Above confluence with San Joaquin River	Time series from CALSIM II output Arc C544	50	4,388	345	Complex concurrent conditions

Table D.1. CALVIN river reaches with environmental flow constraints (cont.)

River	CALVIN links	Location	Data source	Flow values (cubic feet per second [cfs]) Minimum	Maximum	Average	Function of
Yuba	C83_C31	Yuba River at Marysville	SWRCB D-1644 (2001)	250	1,500	494	Year type, Yuba index[e]
Yuba	C28_C29	Yuba River at Smartville	SWRCB D-1644 (2001)	0	700	388	Year type, Yuba index[e]

a. 40-30-30 Sacramento Basin Index: Sacramento River flows that have been weighted in consideration of certain flow periods and antecedent conditions.
b. SJ 60-20-20 Index: San Joaquin River flows that have been weighted in consideration of certain flow periods and antecedent conditions.
c. Shasta Index: Unimpaired inflows into Lake Shasta.
d. Trinity River Index: Unimpaired inflows into Clair Engle Lake.
e. Yuba Index: Based on the Yuba River unimpaired runoff (SWRCB, 2001, for index definition).
Sources: U.S. Bureau of Reclamation (USBR), 1997a; DWR, 1998a, 1993 (for index definitions); SWRCB, 1999 (for Vernalis).

some requirements depend on complex concurrent conditions and, therefore, are calculated during run time in CALSIM II. Because such dynamic calculation is not possible in CALVIN, those minimum flow requirements were taken from the CALSIM II, EWA BST_2001LOD_Gmodel output.

For river reaches outside the CALSIM II network, minimum instream flow requirements were applied where they are known to apply — on, for example, the Yuba River, the Mono Basin, Owens Lake, and the Salton Sea.

With the exception of the Yuba River, the San Joaquin River at Vernalis, the Sacramento River at Hood, and the delta minimum outflow, requirements used for minimum instream flows in the CALVIN model were developed from the minimum flow requirements specified in the input data for CALSIM II, as used in the EWA BST_2001LOD_Gmodel. Monthly minimums, year types, indices, and trigger rules for the requirements were taken from the **.wresl* and **.table* input files of CALSIM II. Requirements that depend on concurrent conditions were taken from CALSIM II output for the EWA BST_2001LOD_Gmodel.

In the CALVIN schematic, delta outflow, 12 rivers, and the inflow into Mono and Owens lakes are required to meet minimum instream flows. Many of the rivers (including the Sacramento, American, Feather, and Tuolumne) have different minimum flow constraints on several reaches. Table D.1 shows the model links on which these constraints are applied and the physical location of these links. Environmental flow requirements have been placed on most major rivers north of the delta and on nearly all major tributaries of the San Joaquin River.

D.1.2 Considerations for instream flow requirements on specific rivers

In representing the various instream flow requirements, several simplifications were necessary to compensate for CALVIN's monthly timestep and network flow optimization requirements. Some watersheds require additional assumptions and calculations, which are described in the sections that follow.

D.1.2.1 Trinity River

The minimum flow requirements on the Trinity River (CALVIN link D94&D40_sink) are based on the Trinity Mainstem Fishery Restoration Environmental Impact Report/Environmental Impact Statement (EIR/EIS) Preferred Alternative. These requirements, listed in Table D.2, depend on the Trinity River Index.

Table D.2. Trinity River minimum instream flow requirements (cfs)

Trinity year type	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	300	300	300	427	4,570	4,626	1,102	450	450	373	300	300
2	300	300	300	460	4,709	2,526	1,102	450	450	373	300	300
3	300	300	300	493	4,189	2,120	1,102	450	450	373	300	300
4	300	300	300	540	2,924	783	450	450	450	373	300	300
5	300	300	300	600	1,498	783	450	450	450	373	300	300

Source: CALSIM II input file *Trinitymin.table.*

D.1.2.2 Clear Creek

Minimum instream flow requirements are applied to Clear Creek below Whiskeytown (CALVIN link SR-3_D73). The minimum instream flow requirements on Clear Creek depend, in part, on Trinity Reservoir storage. Flow stability criteria require that November and December flows equal or exceed October's flow. In addition, Clear Creek flows from February through May should equal or exceed January's flow. Additional fish and wildlife requirements in this reach include CVPIA (b)(2) Anadromous Fisheries Restoration Program (AFRP) Upstream Action #1 and EWA-based assets and asset expenditure. Because of its dependence on complex concurrent conditions, the minimum instream flow requirements used in CALVIN were taken from CALSIM II, model run EWA BST_2001LOD_Gmodel.

D.1.2.3 Sacramento River

Shasta Lake end-of-September minimum storage

The 1993 Winter Run Biological Opinion includes provisions for minimum carryover storage in Shasta Lake (CALVIN node SR-4). The USBR must maintain minimum end-of-September carryover storage in Shasta of 1.9 MAF. The National Marine Fisheries Service (NMFS) and the California Department of Fish and Game (DFG) have judged this carryover storage to be attainable in all but approximately 10% (those considered to be critical and extremely critical water year types). In the period of record of Central Valley Project/State Water Project (CVP/SWP) planning models, this requirement tends to be violated in 1924, during the early 1930s drought, in 1976, in 1977, and during the early 1990s drought. The exact years depend on the particular system operation. In CALVIN, minimum carryover storage in Shasta of 1.9 MAF was imposed in all but the years in which the requirement was not met in the CALSIM II model run EWA BST_2001LOD_Gmodel. In those years the requirement was relaxed to the value simulated in CALSIM II, model run EWA BST_2001LOD_Gmodel.

Upper Sacramento River

Several minimum flow requirements are imposed on various reaches of the Sacramento River. On the upper Sacramento River, the northernmost of these requirements is on the river reach below Keswick Dam (CALVIN link D5_D73). The Sacramento River minimum instream flow requirement below Keswick is, in part, based on the 1993 Winter Run Biological Opinion, and depends on concurrent storage at Shasta Reservoir. These requirements are a proxy for temperature control requirements and do not necessarily guarantee meeting the temperature objectives stated in the 1993 Biological Opinion.

As modeled in CALSIM II, the minimum flow requirement below Keswick is 3,250 cfs in the period from October to August and 6,000 cfs in September. If the beginning-of-month storage at Shasta is less than 2,000 TAF, the September requirement is relaxed to 4,500 cfs. Other relaxation criteria may be in effect based on end-of-March storage at Shasta Reservoir. Furthermore, flow stability criteria require that a fraction of the previous month’s flow must be maintained when flow is below a prespecified threshold in the period from November through April. In addition to these requirements, CVPIA (b)(2) Upstream Action #2 and EWA water also apply in this reach. Because of the dependence on concurrent conditions, the requirements imposed on CALVIN were taken from CALSIM II, model run EWA BST_2001LOD_Gmodel.

On the Sacramento River reach between Red Bluff and Ord Ferry (CALVIN links D76a_D77, D77_D75, D75_C1, C1_C4, and C4_C69), the minimum instream flow requirements depend on the Shasta Index. Table D.3 shows these requirements.

The Navigation Control Point (NCP, CALVIN link D61_C301) is another location on the upper Sacramento River where minimum instream flow requirements are applied. The minimum instream flows in this reach do not aim at satisfying fish and wildlife requirements. Instead, these minimum flows are a result of historical requirements for commercial navigation. Although this river reach no longer supports commercial navigation, water diverters in this reach have installed pump intakes just below the historical navigation minimum flow levels of 5,000 cfs. The operations of these pumps are severely affected if flows drop to 3,500 cfs for more than a few days. In CALSIM II, the minimum flows in this reach depend on Shasta Reservoir levels and the Shasta Index and are set to between 3,500 and 5,000 cfs. To maintain the cold-water pool levels at Shasta Reservoir, the minimum flows at the NCP are relaxed when Shasta storage falls below prespecified threshold levels.

Table D.3. Sacramento River minimum instream flow requirements, Red Bluff to Ord Ferry (cfs)

Shasta Index	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,900	3,250	3,250	3,250
2	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,900	3,250	3,250	3,250
3	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,900	3,250	3,250	3,250
4	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,250	3,900	3,250	3,250	3,250
5	3,000	3,000	3,000	3,000	3,250	3,250	3,250	3,250	3,250	3,000	3,000	3,000

Source: CALSIM II input file *redbluff_base.table.*

Lower Sacramento River

Minimum instream flow requirements on the lower Sacramento River exist at Rio Vista and Hood. The Rio Vista (CALVIN link D507_D509) minimum flow, required under the Water Quality Control Plan D-1641, depends on the Sacramento River Index and is shown in Table D.4. The requirements are changed in February.

The minimum instream flow requirement at Hood (CALVIN link D503_D511) is set to 5,000 cfs.

Table D.4. Sacramento River minimum instream flow requirements, Rio Vista (cfs)

Sacramento River Index	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	0	0	0	0	0	0	0	0	3,000	4,000	4,500	4,500
2	0	0	0	0	0	0	0	0	3,000	4,000	4,500	4,500
3	0	0	0	0	0	0	0	0	3,000	4,000	4,500	4,500
4	0	0	0	0	0	0	0	0	3,000	4,000	4,500	4,500
5	0	0	0	0	0	0	0	0	3,000	3,000	3,500	3,500

Source: CALSIM II input file *riovista.table.*

D.1.2.4 Feather River

Minimum flow requirements in the Feather River are governed by the 1967 agreement between the DWR and the DFG concerning the operation of the Oroville Division of the SWP for management of fish and wildlife. This agreement was amended in 1983 as part of the Federal Energy Regulatory Commission (FERC) re-licensing process.

The 1983 agreement specifies that DWR must release a minimum of 600 cfs into the Feather River from the Thermalito Diversion Dam (CALVIN link C23_C25) for fishery purposes.

Between the Thermalito complex and the confluence with the Sacramento River (CALVIN D42_D43), the agreement between DWR and DFG specifies minimum flow requirements that depend on the percentage of normal runoff[1] and on Lake Oroville’s surface elevation. If Lake Oroville’s surface elevation is greater than 733 feet MSL and the unimpaired runoff is greater than 55% of normal, the requirement for the period from October to March is 1,700 cfs, and the April to September requirement is 1,000 cfs. If, on the other hand, the unimpaired runoff is less than 55% of normal, and Lake Oroville’s surface elevation is greater than 733 feet MSL, the October to February requirement is 1,200 cfs and 1,000 cfs in the period from March to September. When the surface elevation at Lake Oroville is lower than 733 MSL, the March through September requirement is reduced to 750 cfs and the October to February is reduced to 900 cfs.

In addition, if the hourly flow is greater than 2,500 cfs from October 15 through November 30, the flow minus 500 cfs must be maintained until the following March (unless the high flow resulted from flood control operation or mechanical problems). This requirement is designed to protect any spawning that could occur in overbank areas during the higher flow rate by

1. Normal runoff is defined as the mean (1911-1960) April through July unimpaired runoff of 1,942 TAF.

maintaining flow levels high enough to keep the overbank areas submerged. In practice, the flows are maintained below 2,500 cfs from October 15 to November 30 to prevent spawning in the overbank areas.

Because CALVIN cannot dynamically compute these requirements, the time series of minimum flows was taken from CALSIM II, model run EWA BST_2001LOD_Gmodel.

D.1.2.5 Yuba River

The minimum flow requirements on the Yuba River are required under the SWRCB D-1644 (2001) at Marysville (CALVIN link C83_C31) and Smartville (CALVIN link C28_C29). Both flows are dependent on the Yuba River Index, and are shown in Table D.5.

Table D.5. Yuba River minimum instream flow requirements (cfs)

	Wet, above normal, and below normal index > 790		Dry years 630 < index < 790		Critical years 540 < index < 630		Extremely critical years index ≤ 540	
Periods	**Smartville Gage**	**Marysville Gage**	**Smartville Gage**	**Marysville Gage**	**Smartville Gage**	**Marysville Gage**	**Smartville Gage**	**Marysville Gage**
Sept. 15-Oct. 14	700	250	500	250	400	250	400	250
Oct. 15-Apr. 20	700	500	600	400	600	400	600	400
Apr. 21-Apr. 30	—	1,000	—	1,000	—	1,000	—	500
May 1-May 31	—	1,500	—	1,500	—	1,100	—	500
June 1	—	1,050	—	1,050	—	800	—	500
June 2	—	800	—	800	—	800	—	500
June 3-June 30	—	800	—	800	—	800	—	500
July 1	—	560	—	560	—	560	—	500
July 2	—	390	—	390	—	390	—	390
July 3	—	280	—	280	—	280	—	280
July 4-Sept. 14	—	250	—	250	—	250	—	250

Source: SWRCB D-1644 (2001).

D.1.2.6 American River

SWRCB D-893 flow requirements on the American River (CALVIN links D9_D85, D85_D64, and D64_C8). These requirements are based on the 40-30-30 Index and are shown in Table D.6.

In addition to D-893, the Nimbus Dam releases are subject to AFRP actions based on CVPIA (b)(2). These requirements are based on the Folsom Lake end-of-month storage and forecasted Folsom Lake inflow for the remainder of the water year. CALVIN cannot dynamically produce these requirements, so the time series of requirements was taken from CALSIM II, model run EWA BST_2001LOD_Gmodel.

Table D.6. American River minimum instream flow requirements (cfs)

40-30-30 Index	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	250	250	250	250	250	250	250	250	375	500	500	500
2	250	250	250	188	188	188	188	188	281	375	375	500

Source: DWR, 2002.

D.1.2.7 Mokelumne River

The minimum flow requirement on the Mokelumne River is applied on the entire length of the river, between Camanche Reservoir and the confluence with the San Joaquin River (CALVIN links SR-CR_C38, C38_C98, and C98_D517). These requirements are based on the San Joaquin River Index, and are shown in Table D.7.

Table D.7. Mokelumne River minimum instream flow requirements (TAF)

San Joaquin River Index	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	7.7	7.5	6.6	6.6	20	27.8	0	0	0.5	6.3	17.4	13.3
2	7.7	7.5	6.6	6.6	20	27.8	0	0	0.5	6.3	17.4	13.3
3	7.7	7.5	6.6	6.6	20	27.8	0	0	0.5	6.3	17.4	13.3
4	7.7	7.5	6.6	6.6	20	27.8	0	0	0.4	3.6	11.5	8.7
5	2.6	2.4	2.5	0.4	0	0.1	0	0	0.4	0.7	5.5	4.1

Source: CALSIM II input file *minflow_EastSide.table*.

D.1.2.8 Calaveras River

The minimum flow requirement imposed on the Calaveras River applies to the reach below New Hogan Lake (CALVIN link SR-NHL_C40). It is a constant requirement of 0.1 TAF per month.

D.1.2.9 Merced River

Under the Davis-Grunsky (Contract No D-GGR17) agreement with DWR for grant funding of portions of the Merced River Development Plan, the Merced Irrigation District (MID) must provide 180 to 220 cfs flow downstream of the Crocker-Huffman Diversion Dam (CALVIN link D645_D646) to support Chinook salmon spawning runs. Additional minimum flow requirements below the Crocker-Huffman Diversion Dam are to be provided by MID pursuant to water rights adjudication (Cowell Agreement) on the Merced River. Below the dam, MID must make available an amount of water that could then be diverted from the river at several private ditches between the dam and the Shaffer Bridge. These requirements appear in Table D.8.

Table D.8. Merced River minimum instream flow requirements (cfs)

Month	Davis-Grunsky minimum flow below Crocker-Huffman Diversion Dam	FERC 2179 minimum flow at Schaffer Bridge		Cowell Agreement entitlement
		Normal year	Dry year	
October 1-15	0	25	15	50
October 16-31	0	75	60	50
November	180-220	100	75	50
December	180-220	100	75	50
January	180-220	75	60	50
February	180-220	75	60	50
March	180-220	75	60	100
April	0	75	60	175
May	0	75	15	225
June	0	25	15	250
July	0	25	15	225
August	0	25	15	175
September	0	25	15	150

Source: DWR, 2002.

The minimum flow at Shaffer Bridge (CALVIN D649_D695) is governed by MID's FERC license 2179 for operating Lake McClure. Table D.8 shows the minimum flow requirements on the Merced River. A dry year is defined by the FERC license as a forecasted April through July inflow to Lake McClure of less than 450 TAF.

D.1.2.10 Tuolumne River

The minimum flow requirement on the Tuolumne River is based on the San Joaquin Basin 60-20-20 Index and imposed at LaGrange Bridge. The Tuolumne minimum instream flow requirements, which include a base flow and a pulse flow, are shown in Table D.9.

Table D.9. Tuolumne River minimum instream flow requirements (cfs)

	San Joaquin Basin 60-20-20 Index (TAF)						
	<1,500	**1,500**	**2,000**	**2,200**	**2,400**	**2,700**	**>3,100**
Annual volume (acre-ft)	94,000	103,000	117,016	127,507	142,502	165,002	300,923
October 1-15 (cfs)	100	100	150	150	180	200	300
Attraction pulse flow October 1-15 (acre-ft)	None	None	None	None	1,676	1,736	5,950
October 16-May 31 (cfs)	150	150	150	150	180	175	300
Out-migration pulse flow April 15-May 15 (acre-ft)	11,091	20,091	32,619	37,060	35,920	60,027	89,882
June 1-September 30 (cfs)	50	50	50	75	75	75	250

Source: DWR, 2002.

D.1.2.11 Stanislaus River

The fishery flow requirements on the Stanislaus River comprise a prespecified minimum base flow below Goodwin Dam and a pulse flow between April 15 and May 16. The minimum flow below Goodwin Dam is governed by the 1987 agreement between USBR and DFG and the New Melones Interim Operations Plan, and is based on hydrologic conditions in the Stanislaus River basin.

The annual fishery flow allocation on the Stanislaus River varies between 0 TAF and 467 TAF, depending on the New Melones conditions. These conditions are computed as end-of-February storage in New Melones plus the forecasted March through September inflow into New Melones. Table D.10 shows the annual fishery allocation as a function of storage plus forecasted inflow (New Melones condition).

Once the annual fishery allocation is determined, another lookup table is used to compute the monthly base flow (Table D.11).

In addition to the base fishery flows, the USBR must provide pulse flows on the Stanislaus River between April 15 and May 16. These pulse flows, also a function of the Stanislaus River annual fishery allocation, are shown in Table D.12.

Table D.10. Stanislaus River annual fishery flow allocation

New Melones condition (TAF)	0	1,400	2,000	2,500	>3,000
Annual fishery allocation (TAF)	98	98	125	345	467

Source: CALSIM II input file *stan_yr.table.*

Table D.11. Stanislaus River minimum instream flow requirements (cfs)

Annual fishery allocation	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	0	0	0	0	0	0	0	0	0	0
98.9	125	125	125	250	250	0	0	0	0	110	200	200
155	150	150	150	300	300	125	125	125	125	110	225	225
200.6	250	250	250	300	300	200	200	200	200	200	250	250
256.2	275	275	275	300	1,500	200	200	200	200	250	275	275
311.5	300	300	300	900	900	250	250	250	250	250	300	300
410.2	350	350	350	1,500	1,500	800	300	300	300	350	350	350
>466.4	400	400	400	1,500	1,500	825	625	525	400	350	400	400

Source: CALSIM II input file *stan_monfish.table.*

Table D.12. Stanislaus River pulse flow requirements (cfs)

Annual fishery allocation	Pulse flows
0	0
98.9	500
245.7	1,500

Source: CALSIM II input file *stan_pulse.table.*

The time series of minimum flow requirements used in CALVIN was developed using the time series of inflows to New Melones and the end-of-month storage in New Melones, as modeled in CALSIM II, model run EWA BST_2001LOD_Gmodel.

D.1.2.12 Mono Basin

From a water supply perspective, two tiers of environmental constraints exist in the Mono Basin, which aggregates the inflow from Rush, Parker, Walker, and Lee Vining creeks. Each creek has an instream flow requirement, as directed in SWRCB Decision 1631. In addition to the instream flow requirement, the City of Los Angeles is required to maintain a Mono Lake elevation of 6,391 feet above MSL or accept a reduced diversion schedule as specified in SWRCB Decision 1631. Considering minimum instream flow requirements only, approximately 45 TAF/yr of Mono Basin water is available for supply and power generation for the period from October 1921 to September 1993. When also taking Mono Lake refilling needs into account, DWR (1998b) estimates that the Mono Basin can supply the City of Los Angeles with 31 TAF/yr after lake-level requirements are satisfied.

Instead of determining which SWRCB flow schedule to use, CALVIN requires Mono Lake to reach 6,391 ft above MSL (or 2,939 TAF according to area-elevation-capacity relationships provided in Vorster, 1983) at the end of every March (the beginning of the Eastern Sierra Nevada water year). CALVIN assumes that this elevation has been reached in 2020 and that the City of Los Angeles can divert water from the Mono Basin subject to minimum instream flow constraints as long as the specified lake level is maintained.

The only outflow from Mono Lake is evaporation. Annual figures from Vorster (1983) were converted to monthly values with the assumption that Mono Lake has the same evaporation pattern as Lake Isabella on the Kern River. These figures are net evaporation, which account for precipitation and inflow to Mono Lake from sources other than Rush, Parker, Walker, and Lee Vining creeks.

D.1.2.13 Owens Lake

As a result of recent litigation, the City of Los Angeles is required to take air quality remediation measures in the dry Owens Lake bed. Excessive surface water withdrawals and groundwater pumping in the region have caused dust storms with very high levels of particulate matter. To alleviate this problem, the city is required to carry out one of three combinations of remediation techniques: (1) shallow flooding of the lake bed, which requires 4 acre-ft of water per acre; (2) managed vegetation, which requires 2 acre-feet of water per acre; or (3) gravel coverage, which requires no water (see Table D.13). GBUPCD (1998) assumed a mix of alternatives that would require 51 TAF/yr. This is reflected in the Table D.13 calculations and is represented as a fixed diversion in CALVIN. Ono (1999), however, suggests that the City of Los Angeles might choose a combination of alternatives that would lower the total water requirement to only 40 TAF/yr. As shown in Table D.13, this is the requirement imposed in CALVIN.

Table D.13. Water requirements for Owens Lake remediation[a,b]

Month	Managed vegetation (TAF/month)	Shallow flooding (TAF/month)[c]	Total Owens Lake requirement (TAF/month)	CALVIN requirements (TAF/month)
October	0.7	1.9	2.5	2.04
November	0.4	1.2	1.6	1.47
December	0.4	1.2	1.6	0.95
January	0.5	1.5	2.0	1.99
February	0.9	2.7	3.6	1.24
March	1.4	4.0	5.4	1.26
April	2.0	5.7	7.7	1.6
May	2.5	7.3	9.8	2.8
June	2.9	8.2	11.1	4.2
July	2.6		2.6	6.05
August	1.9		1.9	7.69
September	1.2		1.2	8.7
Total			**51**	**40**

a. Assuming the City of Los Angeles selected the following control measures: 8,400 acres of shallow flooding, 8,700 acres of managed vegetation, and 5,300 acres of gravel.
b. Assuming the same evaporation pattern as Lake Isabella on the Kern River.
c. No flooding is required between August 1 and September 14 (the whole month of September neglected in CALVIN).

D.1.2.14 Sacramento-San Joaquin Delta outflow

Minimum instream flows within the Sacramento-San Joaquin Delta have not been modeled explicitly for each river within the delta. Instead, minimum flows through the delta are guaranteed with a single minimum outflow requirement into the San Francisco Bay.

X2, the location of the 2 parts per thousand isohaline, is used to identify the estuarine entrapment zone. Various U.S. Environmental Protection Agency (EPA) X2 requirements greatly affect the delta outflow constraint. CALSIM II uses various methods to calculate the X2 position, which changes the monthly total outflow constraint. Because CALVIN lacks the ability to make an X2 calculation, CALVIN’s delta outflow constraint is the minimum delta outflow time series resulting in DWRSIM Run 514 as fixed flow requirements.

D.1.2.15 Salton Sea

Although no water supply is available from the Salton Sea, it is included in the CALVIN schematic to maintain a physical representation and because it is a major focus of concern in the South Lahontan hydrologic region. Return flows are the only CALVIN inflows included in the Salton Sea and the only outflow is evaporation. Although the New and Alamo rivers are represented on the network schematic diagram (Figure 6-3 and 6-4 in the CALVIN report), these rivers have zero inflows because they are used only for limited industrial water purposes (Montgomery Watson, 1996).

Although detailed area-elevation-capacity relationships exist for the Salton Sea, CALVIN cannot mimic the results of more detailed water balance simulation models.

Monthly figures for the Salton Sea were obtained from Hughes (1967) and Ferrari and Weghorst (1995). Because these values were given for inconsistent time increments (15-32 days), monthly evaporation was roughly estimated based on the corresponding dates. Hughes (1967) found annual evaporation to be around 72 inches per year, but the currently accepted value is 66 inches per year. Accordingly, the values in Hughes (1967) and Ferrari and Weghorst (1995) were normalized to equal 66 inches per year.

D.1.2.16 San Joaquin River

The Final Environmental Impact Report for Implementation of the 1995 Bay/Delta Water Quality Control Plan (SWRCB, 1999) is the source for the required pulse and X2 flow data at Vernalis. Technical Appendix 4 of the SWRCB Report provides a monthly time series (DWRSIM run 1995C06F-SWRCB-469, November 96) of required minimum flows for water years 1922 through 1994 at the 1995 level of development. The required flows at Vernalis are based on the San Joaquin Valley 60-20-20 Index for determination of water year type and the Eight River Index. The unimpaired runoff from the four Sacramento River Index rivers and the four San Joaquin River Index rivers is summed to produce the Eight River Index (DWR, 1998b). The previous month's Eight River Index (or PMI) is used to indicate how many days the Delta X2 standard must be maintained at a specified location such as Chipps Island (Table D.14) during the current month. The months from February through June are regulated by the X2 standard.

Table D.14. Days maximum daily average EC of 2.64 mmhos/cm must be maintained[a]

PMI[b] (TAF)	Chipps Island				
	February	March	April	May	June
≤500	0	0	0	0	0
750	0	0	0	0	0
1,000	28	12	2	0	0
1,250	28	31	6	0	0
1,500	28	31	13	0	0
1,750	28	31	20	0	0
2,000	28	31	25	1	0
2,250	28	31	27	3	0
2,500	28	31	29	11	1
2,750	28	31	29	20	2
3,000	28	31	30	27	4
3,250	28	31	30	29	8
3,500	28	31	30	30	13
3,750	28	31	30	31	18
4,000	28	31	30	31	23
4,250	28	31	30	31	25
4,500	28	31	30	31	27
4,750	28	31	30	31	28
5,000	28	31	30	31	29
5,250	28	31	30	31	29
≥5,500	28	31	30	31	30

a. The 2 ppt isohaline (X2) is measured as 2.64 mmhos/cm surface salinity.
b. PMI is the best available estimate of the previous month's Eight River IndexNote: Linear interpolation is used to determine the number of days for values of the PMI between those specified.
Source: SWRCB, 1999, Table II-4.

Minimum flows at Vernalis from February through June (Table D.15) are described as meeting either high or low objectives depending on the required X2 position (Table D.14). The higher flow is required when the X2 position is at or downstream of Chipps Island, and the lower flow is allowed when the X2 position is upstream of Chipps Island. The water year type (San Joaquin 60-20-20 Index) determines the high and low flow quantities.

Minimum flows at Vernalis during the month of October follow unique rules. For all water years, the minimum flow is 1,000 cfs plus up to a 28 TAF (455 cfs) pulse flow. Application of this pulse flow results in a minimum flow for October that usually depends on the actual flow at Vernalis (Table D.16). The required minimum flow ranges from 1,455 cfs to a maximum of 2,000 cfs, with one exception. If a critical year follows a critical year, the 28 TAF pulse flow is not required and the minimum flow for October is 1,000 cfs.

Minimum required flows at Vernalis for the months of January, July, August, September, November, and December are zero. As South Delta water quality and quantity needs are determined, these six unregulated months could be affected.

Table D.15. February-June minimum flows at Vernalis (cfs)

Year type	February 1-April 14 and May 16-June 30	April 15-May 15
Wet	2,130 or 3,420	7,330 or 8,620
Above normal	2,130 or 3,420	5,730 or 7,020
Below normal	1,420 or 2,280	4,620 or 5,480
Dry	1,420 or 2,280	4,020 or 4,880
Critical	710 or 1,140	3,110 or 3,540

Source: SWRCB, 1999, Appendix 2.

Table D.16. October minimum flows at Vernalis (cfs)

Actual flow	Required flow
<1,000	1,455
1,000-1,545	Actual flow + 455
≥1,545	2,000

Source: SWRCB, 1999, Appendix 2.

D.2 Fish and Wildlife Refuge Demands

California's refuge areas have been consolidated into six refuge nodes: the Sacramento East, Sacramento West, San Joaquin, Mendota, Kern, and Pixley refuges. Each of these areas has distinct environmental water supply requirements. The requirements for all refuges are based on Level 4 refuge requirements, as stated in the various EIR/EIS pertaining to each refuge (USBR, 1997b, c, d, e, and f). The monthly refuge requirements for these water districts can be found in the appropriate EIR/EIS. Tables D.17 and D.18 summarize CALVIN's representation of fish and wildlife Level 4 refuge demands.

Table D.17. CALVIN deliveries to fish and wildlife refuges

				Deliveries (TAF/month)		
Aggregate refuge	**Sources**	**Link**	**Refuges included**	**Minimum**	**Maximum**	**Average**
Kern	USBR, 1997e	C95_KERN REFUGES	Kern NWR	0.5	4.4	2.4
Pixley	USBR, 1997e	C60_PIXLEY NWR	Pixley NWR	0	0.8	0.5
Sacramento west refuges[a]	USBR, 1997d	C302_SAC W REF	Sacramento, Delevan, and Colusa NWR	1.6	22.8	11.7
Sacramento east refuges[a]	USBR, 1997b	C311_SAC E REF	Sutter and Gray Lodge NWR	2.8	15.0	7.0
San Joaquin	USBR, 1997c	D723_San Joaquin Refuges	Volta WMA Freitas SJBAP Salt Slough SJBAP China Island SJBAP	1.8	8.9	3.9
Mendota Wildlife area	USBR, 1997f	D732_Mendota Wildlife Area	Grassland WD Los Banos WMA Kesterson NWR San Luis SWR Mendota WMA Merced NWR West Gallo SJBAP	12.1	67.0	28.8

a. Sacramento West and East Refuge deliveries are reported as volumes of water delivered into the refuge. Conveyance losses have already been taken into account.
Notes:
SJBAP = San Joaquin Basin Action Plan.
NWR = National Wildlife Refuge.
SWR = State Wildlife Refuge.
WMA = Wildlife Management Area.

Although Level 2 supply to refuges is subject to the same deficiency criteria as the exchange contractors (a 25% cut in years in which the Shasta criteria is critical), the increments to Level 4 are not subject to deficiencies. Therefore, the Level 4 refuge demand, as implemented in CALVIN, was computed as the firm Level 2 demand, subject to 25% decrease when the Shasta criteria is critical, plus the full increment to Level 4.

Deliveries to most refuges are subject to conveyance losses. The aggregate conveyance losses for each consolidated refuge node are shown in Table D.19. Pixley NWR is unusual in that its Firm Level 2 supply comes entirely from wells located within the refuge boundaries. Therefore, its Level 2 demand is subject to neither a deficiency nor conveyance loss. Its increment to Level 4, on the other hand, comes from surface water sources, and is thus subject to conveyance losses (15%).

Table D.18. Level 4 fish and wildlife refuge demands (TAF/year)

Aggregate refuge	Annual delivery	Conveyance loss	Annual diversion	Loss (%)
Sacramento west refuges	105	35	140	25
Sacramento east refuges	74	10.3	84.3	12
Mendota Wildlife area	290.5	55.4	345.9	16
San Joaquin area refuges	41.7	5.4	47.1	11
Kern	25.0	3.7	28.7	13
Pixley	4.7	.83	5.5	15

D.3 Summary

CALVIN includes 12 minimum instream flows, 6 refuge nodes, Shasta carryover storage, minimum bay delta outflows, and the Mono-Owens minimum as environmental requirements in the system. Average annual environmental requirements are shown in Table D.19.

Table D.19. Summary of environmental requirements

	Average annual requirement (TAF/yr)
Minimum instream flows	
Trinity River	599
Clear Creek	122
Sacramento River below Keswick	4,069
Sacramento River between Red Bluff and Ord Ferry	2,393
Sacramento River at NCP	3,293
Feather River below Oroville	434
Feather River below Thermalito return	862
Yuba River at Smartville	280
Yuba River at Marysville	358
American River below Nimbus	1,398
American River below urban diversions	228
Mokelumne River	88
Calaveras River	1
Sacramento River at Hood	3,620
Sacramento River at Rio Vista	941
Stanislaus River	265
Tuolumne River below Don Pedro Reservoir	119
Tuolumne River below Turlock ID diversion	279
Merced River below Crocker-Huffman Diversion Dam	118
Merced River at Schaffer Bridge	79
San Joaquin River at Vernalis	1,031
Refuge requirements[a]	
Sacramento west refuges	140
Sacramento east refuges	84
Mendota refuges	346
San Joaquin	47
Pixley	5
Kern	29
Bay Delta outflow	
Bay Delta	5,593

Table D.19. Summary of environmental requirements (cont.)

	Average annual requirement (TAF/yr)
Mono/Owens requirement	
Mono Lake inflows	74
Owens Lake dust mitigation	40
Shasta carryover storage	1,900 TAF

a. Including conveyance losses.

D.4 Limitations

Environmental benefits are not modeled explicitly in CALVIN. Only the benefits associated with the included constraints, minimum instream flow constraints, and fish and wildlife refuges may be analyzed from the perspective of urban and agricultural water users. Environmental water use is not optimized.

Environmental flows in the Sacramento-San Joaquin Delta have been simplified. Flows on individual river reaches within the have not been modeled explicitly.

The environmental flow requirements for some river reaches involve complex operating rules that cannot be easily represented as a simple time series. In many cases, therefore, the time series used in CALVIN is based on an assumed system operation that does not necessarily correspond with the operation recommended by the model.

The refuges represented in the model are aggregations of many, much smaller refuge areas. These aggregations may allow the model to make refuge deliveries more efficiently than is actually possible.

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Appendix VII — Attachment E

Miscellaneous Revisions for CALVIN Model

In addition to creating an initial set of new supply links for each of the new urban economic demands created for 2100, we made the modifications outlined in this attachment.

Table E.1. List of local supply modifications to CALVIN for 2100 demands and perturbed hydrologies

New Links with UPPER BOUNDS = 0:

C173_T43 UB = 0, cost $50

New and old links with modified UPPER BOUNDS:

a. Mallard PMP_C71 set back to UBMonthly of about 3 taf/mo. cost 299

b. GW-SCV_T7, from previous 30.5 to 45.7 (raised 50% for 2100 demands)

c. D662_T66 set to Ag capacity for D662 to CVPM 12 ($50 cost) (UB = 107.1)

d. C65_T53, Delano (CVPM 20 urb) set to ag capacity for C65 to CVPM 20 ($50 cost) UB = 79.2

e. FKC C688_T51 and C56_T51 Kaweah (urban CVPM 18 Visalia) set to ag link upper bound and $50 cost

Existing links with unconstrained Upperbounds (change constraint method to “none” for upper bound):

a. GW-21_T28 & D850_T28 (Bakersfield)

b. D16_T45 & D662_T45 (Modesto)

c. C74_C97 & C74_HSU20C74 (Cross Valley canal deliveries to CVPM 19 and 20)

d. C689_C65 (FKC wasteway to Kern River)

e. D689_HSU11, D664_HSU11, & D672_HSU11 (SW supplies for CVPM 11 from San Joaquin, lower Tuolemne and lower Stanislaus)

f. C49_T24 (Fresno Urban supply from FKC)

g. D606_HSU16 (San Joaquin R supply to CVPM 16 AG)

h. D645_T66 (Merced to Turlock CVPM 12 Urb)

i. D848_D849 (Coastal Aqueduct ending capacity of 71 cfs or 3.94-4.3 taf/mo turned off)

j. T11_C158, wastewater recharge to lower Coachella valley, set to unconstrained (constraint on total recharge capacity C158_GW-CH)

k. SR-28_C106 and SR-29_C106

Table E.1. List of local supply modifications to CALVIN for 2100 demands and perturbed hydrologies (cont.)

New links with unconstrained capacity:

a. D871_T3 (Mojave SWP direct use); cost would be $349 unconstrained

b. C136_T31 (CRA to Coachella direct use) unconstrained, cost = 251

c. Add new node HWTC147, and links C147_HWTC147, HWTC147_T31 (Coach Canal direct to Coachella Urban) unconstrained, cost = 372